



INSTITUTE FOR DEFENSE ANALYSES

Effect of the Proposed Closure of NASA's Subsonic Wind Tunnels: An Assessment of Alternatives

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Preface

The Institute for Defense Analyses (IDA) prepared this document for the Office of the Director of Operational Test and Evaluation, under a task titled “Resource Analysis for Test and Evaluation.” The task objective is to conduct analyses that lead to improved planning and programming of test resources. This document partially fulfills that objective by assessing the effect of closing subsonic wind tunnels at NASA’s Ames Research Center on the Department of Defense (DoD) and providing alternatives to either prevent the closures or mitigate adverse effects.

John J. Cloos, Christopher A. Martin, Thomas A. Musson, and Robin B. Sellers of IDA were the technical reviewers for this document.

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Summary

Background

In the spring of 2003, the National Aeronautics and Space Administration (NASA) announced its decision to inactivate three subsonic wind tunnels at the Ames Research Center in California. Two of those tunnels, the 40 × 80-foot tunnel and the 80 × 120-foot tunnel that comprise the National Full-Scale Aerodynamic Complex (NFAC), are the largest and second largest wind tunnels in the world. The third tunnel is known as the 12-Foot Pressure Wind Tunnel.

If sufficient workload does not materialize by the end of fiscal year 2004 to allow those tunnels to remain open on a self-sustaining basis, NASA plans to close them permanently. The decision to close the wind tunnels took place while NASA was implementing a policy of recovering the full costs of operating and maintaining test facilities from customers of those facilities. The full-cost-recovery policy is a departure from previous NASA financial practices.

The Office of the Secretary of Defense became concerned about the effect of the NASA decision on the Department of Defense. In the late spring of 2003, the Director of Operational Test and Evaluation tasked the Institute for Defense Analyses (IDA) to assess the effect that the closure of the subsonic wind tunnels at the Ames Research Center would have on the DoD. IDA was also to provide a prioritized list of alternatives available to either prevent the closures or mitigate any resulting adverse effects on the department. As a collateral matter, IDA was asked to ascertain whether there was a direct correlation between NASA's implementation of a full-cost-recovery policy and declining utilization of the three subsonic wind tunnels.

Scope of Effort

IDA reviewed the history of the relationship between the DoD and NASA with respect to wind tunnels, from both a functional and a financial perspective, and identified the factors responsible for NASA's decision to inactivate the wind tunnels at Ames. We then assessed the implementation and effect of NASA's full-cost-recovery policy. We also investigated the means by which DoD components and the U.S. aerospace industry have been conducting subsonic wind tunnel testing during the period leading up to the closure of the tunnels at

Ames. Finally, we analyzed options for testing in the future. Particular emphasis was given to the rationale for conducting wind tunnel tests in foreign countries, since the practice was found to be prevalent. We delineate eight alternatives that are available to the DoD to respond to the actions that NASA has taken. Each alternative is analyzed so that the foreseeable consequences of selecting the alternative are identified for DoD officials.

Findings

We found the closure of the subsonic wind tunnels at the Ames Research Center resulted from several factors:

- The number of “new starts” in aircraft development in the United States has drastically declined in recent years.
- The number of defense contracts involving large/full-scale wind tunnel testing has declined.
- All three of the affected tunnels at the Ames Research Center were closed for repairs and renovations for extended periods of time during the 1990s, causing customers to conduct their wind tunnel testing in alternate facilities, where those customers sometimes established satisfactory experience and large databases. Changing tunnels after the NASA tunnels reopened would result in increased cost and technical risk for some programs.
- Some DoD components and U.S. aerospace companies have elected to take their wind tunnel testing work to facilities outside the United States.
- NASA’s decision to curtail funding for rotorcraft research has left its partner, the U.S. Army, unable to finance the resulting shortfall and support large-scale helicopter research and development.
- NASA’s implementation of its full-cost-recovery policy has caused some wind tunnel testing work to be withdrawn from the wind tunnels at Ames and either abandoned or taken to facilities where testing could be accomplished at a lower cost to the customer.

Prior to starting the full-cost recovery initiative in 1995, NASA provided wind tunnel services to DoD components generally without charge. On the other hand, DoD organizations designated as part of the Major Range and Test Facilities Base¹ operate under a policy that charges DoD customers (generally

¹ The Major Range and Test Facility Base comprises 19 broad-based test and evaluation facilities/ranges that are managed and operated primarily to provide support to the DoD components responsible for developing or operating materiel and weapon systems. Testing is available to non-DoD customers at higher costs.

acquisition programs) only the direct costs of using their test facilities and ranges and charges non-DoD Federal customers, as well as defense contractors, direct costs plus an appropriate amount of indirect costs.

In the 1970s, the U.S. Air Force conducted a short-lived experiment in charging its customers full costs for using wind tunnels. The experiment discouraged many customers from performing their test programs and left the test center without sufficient customer reimbursements to meet its operating expenses.

Regarding NASA's recent financial policy change, we were unable to establish a direct cause-and-effect relationship between NASA's gradual implementation of full-cost recovery and declining utilization of the subsonic wind tunnels at the Ames Research Center. However, the policy seems to have been a contributing factor. Two recent reports, which are quoted in Chapter V, indicate that such a policy will lead to loss of customers and ultimately to closure of a facility.² Therefore, if NASA's full-cost-recovery program continues, use of other NASA aeronautical test facilities can be expected to decline and additional facilities may be closed.

Interagency agreements, specifically those forming the Aeronautics and Astronautics Coordinating Board and the National Aeronautical Test Alliance, provide for coordination between NASA and the DoD in an integrated strategy for the management of aeronautical test facilities. These agreements were ineffective in preventing the closure of three major test facilities of importance to the DoD.

The use of foreign facilities for the conduct of wind tunnel tests is now commonplace among DoD components and the U.S. aerospace industry. Much of that test work is being performed in Western Europe. There are some advantages to conducting testing in foreign facilities. Several of those facilities are more modern and productive than the tunnels that NASA is closing. Sometimes the quality of testing abroad may be higher, availability may be greater, and the price of testing may be lower. In addition, one major program, the Joint Strike Fighter (JSF), is an international aircraft development effort, to which other nations contributed by providing wind tunnel testing. Initially, this may appear to be beneficial to U.S. programs. However, there are disadvantages to foreign testing. It is highly unlikely that the DoD or the U.S. aerospace

² The report of the Commission on the Future of the U.S. Aerospace Infrastructure and Aerospace Engineering Disciplines to Meet the Needs of the Air Force and the Department of Defense as well as a report of the Rotorcraft Subcommittee of NASA's Aerospace Technology Advisory Committee.

industry will be able to conduct *full-scale* testing of aircraft in any foreign wind tunnel, and the use of smaller wind tunnels will result in less accurate simulation of flight conditions. If U.S. entities become dependent on specific foreign wind tunnels, a virtual sole-source situation could materialize, and the U.S. entities may find their access to such facilities limited for economic or political considerations. Similarly, once a sole-source situation has been created, U.S. entities using foreign facilities would be vulnerable to significant price increases due to the absence of a competitive marketplace. Finally, because of the competitive nature of aeronautical development, a number of DoD personnel and representatives of U.S. aerospace companies have expressed concerns about the inherent risks of compromising test data and experimental aircraft designs when using some foreign facilities. Those concerns are intensified because the Europeans have publicly stated their strategic objective of attaining global leadership in aeronautics by the year 2020.

Finally, during the research phase of this study, we were apprised of a provision of the Code of Federal Regulations providing that no fee will be charged for industry work on Government projects in NASA wind tunnels. That provision appears to be inconsistent with the implementation of full-cost recovery.³

Effect of Closure of NFAC and the 12-Foot Pressure Wind Tunnel

The principal effect on the DoD of NASA's closure of its full-scale wind tunnels at the NFAC is the likely negative impact on rotorcraft research in the United States. This comes at a time when new rotorcraft missions and requirements are emerging in both national defense and homeland security.

Other effects, related to both the NFAC and the 12-Foot Pressure Wind Tunnel, are that aircraft developers will need to use foreign facilities for development of advanced military systems requiring low-speed testing. Dependence on foreign facilities can jeopardize timely and affordable access to testing and sometimes could result in lesser test capability. In addition, foreign exposure will place our newest and most technologically advanced systems at risk for the compromise of design information.

As a result of the inactivation of the subsonic wind tunnels at the Ames Research Center, both Government and contractor personnel have been either reassigned or separated. The resulting loss of expertise in research, development,

³ NASA is attempting to update the Code of Federal Regulations.

and test and evaluation, on the one hand, and wind tunnel maintenance and operations, on the other, will make recovery difficult and time-consuming.

It is also foreseeable that researchers will be compelled to use smaller wind tunnels (with a resulting loss of data fidelity) and earlier flight-testing to investigate full-scale aerodynamic effects. Those practices can increase the cost and risk of developing both fixed-wing and rotary aircraft.

The closure of the wind tunnels at the Ames Research Center, contributes to U.S. dependence on foreign facilities. Some industry experts, such as the Executive Director of the American Helicopter Society International and the Chairman and CEO of Bell Helicopter, believe the U.S. rotorcraft industry may find itself particularly disadvantaged vis-à-vis European competitors.

Efficacy of Intra-Governmental Agreements and Organizations

The agreements in place between NASA and the DoD, the arrangements they established, and the organizations they created were ineffective in preventing the inactivation of the subsonic wind tunnels in this case. DoD activities did not even receive timely notice of the inactivation.

Preventing Closure of the Subsonic Wind Tunnels at Ames

Since NASA has inactivated the subsonic wind tunnels and stands prepared to close them permanently, we explored the avenues available to the DoD to either prevent permanent closure of the facilities or at least ameliorate the effects of those closures. As a result, we identified eight alternatives that the DoD could implement, or at least initiate, in the near term. In addition, we provided two long-range options. Those options are not substitutes for adopting one of the alternatives, but they could be pursued while one of the alternatives is put in place to deal with the immediate effects of the closures. Successful implementation of either of those options would require support from activities outside the DoD and NASA, and would require many years to accomplish.

Alternatives

The alternatives available to the DoD were developed taking several factors into consideration, including the age and condition of the wind tunnels at the Ames Research Center, their geographical location, the lead time required for implementation of each alternative, and the advantages and disadvantages of pursuing each proposed course of action. The 40 × 80-foot tunnel was placed in operation in 1944, and the 80 × 120-foot tunnel was added in 1982. Although both tunnels have been upgraded somewhat since construction, they could benefit

from completion of some deferred maintenance, and they could be modernized to achieve greater productivity. The 12-Foot Pressure Wind Tunnel was placed in operation in 1946. It was rebuilt in the 1990s, albeit to the original configuration. In addition, urban development and population growth in the vicinity of the Ames Research Center have taken place since the wind tunnels were constructed, and the availability and cost of power have become factors in wind tunnel management at that location.

Although we identified eight alternatives, we recommend adoption of one of the first three. The three recommended alternatives, which are ranked in order of priority, with the most highly recommended alternative first, are briefly described below:

- **Assume ownership of or lease the NFAC (and possibly the 12-Foot Pressure Wind Tunnel), assume operational responsibility, and upgrade the facilities to meet current and future needs.** This alternative preserves the country's investment in these unique national assets, leaves them available to the DoD and the U.S. aerospace industry as well as NASA, and avoids less desirable alternatives such as replacing the facilities or increasing dependence on foreign test facilities. The cost of upgrading would depend on the number and types of investments selected. However, an upgrade such as replacing the existing fan blades would extend the life of the drive system and permit testing at or near full speed without risk of a drive system failure. Other enhancements such as modernized data acquisition systems would make the tunnels more productive.
- **Prevail upon NASA to continue to maintain and, as necessary, operate the large/full-scale subsonic wind tunnels (and possibly the 12-Foot Pressure Wind Tunnel) at the Ames Research Center.** Like the first alternative, this alternative preserves the public investment in the wind tunnels. It involves minimal disruption of existing arrangements, although it is contingent upon implementation of a funding mechanism that would permit the tunnels to be maintained and operated as necessary. We recommend that customers be charged direct costs of their wind tunnel tests, with the remaining costs to maintain the facilities provided through a direct appropriation to NASA.
- **Assume ownership of or lease the NFAC (and possibly the 12-Foot Pressure Wind Tunnel) and assume operational responsibility without upgrading or modifying the facilities.** As a short-term solution, this has many of the same benefits and advantages as the first alternative. National assets are preserved, and the door is open for critical rotorcraft and fixed-wing research and development to resume with a minimum of additional investment. The failure to correct existing known deficiencies

in the facilities would result in less use, lower data fidelity for some tests, and a shorter useful life for the facilities.

The other five, less-desirable alternatives described in the report are:

- Construction of state-of-the-art subsonic wind tunnels using military construction appropriations, which would involve considerable expense and require a long time to accomplish.
- Use of alternative wind tunnels in the United States, which degrades the quality of testing though the use of smaller scale models and testing at lower Reynolds numbers.
- Use of alternative wind tunnels in foreign countries, which may result in a dependency relationship in which U.S. customers could face loss of timely access, non-competitive pricing, and potential security risks.
- Greater reliance on computational modeling and simulation, which results in a greater risk of misleading or incorrect results than wind tunnel testing.
- Maintenance of the status quo, in which case the subsonic wind tunnels at the Ames Research Center are likely to be closed permanently, the trend toward use of foreign wind tunnels can be expected to continue, and rotorcraft and tilt-rotor development in the United States could be adversely affected, slowing technological progress, and reducing the competitiveness of U.S. firms.

Long-Range Options

In addition to the alternatives described above, IDA considered two long-range solutions that would take several years to implement and would require support from organizations other than NASA. Neither one of the options, described below, should be considered a substitute for adopting one of the alternatives.

- **Establish an independent agency with ownership and operational responsibility for major U.S. aerospace test facilities.** One potential long-range solution might be the creation of a new national testing agency, which owns and operates the major U.S. aerospace test facilities. This independent agency would be funded by Congress and provide services to both military and civil research and development. This is not a new idea; it has been discussed, but not pursued, in the past. However, circumstances as they appear today could make the proposal more feasible.
- **Privatize the inactivated subsonic wind tunnels or transfer operational responsibility to a non-Federal organization.** Another possible long-range solution would be to persuade NASA to turn ownership and/or

operational responsibility for the inactivated subsonic wind tunnels at the Ames Research Center over to a non-Federal organization in the private sector, academia, or a consortium. Although the successful implementation of this option has the potential to preserve unique national assets, the option involves inherent risks that decision makers need to consider.

Recommendations

Our recommendations for the DoD are as follows:

- **Select an Alternative.** Select and implement Alternative 1, 2, or 3 as soon as practicable.
- **Formalize Forecasting.** Establish a formal process for DoD components to forecast their future requirements for use of NASA's aeronautical test facilities and communicate those forecasts to NASA.
- **Review International Cooperation Policies and Practices.** Review DoD policies and practices regarding international cooperation in test and evaluation programs to ensure that they are consistent with national objectives and provide for adequate security.
- **Review DoD-NASA Interagency Agreements.** Review the efficacy of existing interagency agreements between the DoD and NASA with respect to major test facilities. The review should address their utility, cost-effectiveness, and enforceability.
- **Assess the Complete Effect of NASA's Full-Cost-Recovery Policy.** Conduct an assessment of the effects of NASA's full-cost-recovery policy on DoD components. The assessment should include prospective closures of aeronautical test facilities in other flight regimes as well as the effects on the programs and the budgets of DoD components.
- **Determine if Application of Full-Cost Recovery to Government Projects Violates the Code of Federal Regulations.** Request that the DoD General Counsel assess the applicability of Section 1210, Title 14, of the Code of Federal Regulations to fees assessed by NASA for wind tunnel testing provided in support of Government projects. If the current NASA policy violates the Code of Federal Regulations, request that NASA modify its policy to bring it into compliance.⁴

⁴ As previously noted, NASA is attempting to update the Code of Federal Regulations.

I. Introduction

This report summarizes our assessment of the effect on the Department of Defense (DoD) and the U.S. aerospace industry if the National Aeronautics and Space Administration (NASA) were to permanently close its large-scale subsonic wind tunnels at the Ames Research Center. It also provides an analysis of alternatives available to the DoD in the event that the closure actually materializes.

A. Study Background

In the spring of 2003, NASA announced its decision to inactivate three subsonic wind tunnels at the Ames Research Center in Mountain View, California. Two of those tunnels are the largest and second largest wind tunnels in the world. Together, they comprise the National Full-Scale Aerodynamic Complex (NFAC). The older of the two, the 40×80 -foot tunnel, has been used to test various aircraft for NASA, the DoD, and other customers for nearly 60 years. The larger of the two, the 80×120 -foot tunnel was added in 1983. The third facility is a pressurized wind tunnel known as the 12-Foot Pressure Wind Tunnel. Originally built in 1946, it was refurbished in the early 1990s and restored to service in 1995. That tunnel permits the study of aircraft configurations at low speed and high Reynolds number with small-scale models.

In the late spring of 2003, the Director of Operational Test and Evaluation tasked the Institute for Defense Analyses (IDA) to assess the effect that the closure of the subsonic wind tunnel facilities at the Ames Research Center was likely to have on the DoD. IDA was to provide a prioritized list of alternatives available to either avoid closure or ameliorate the effects of closure. As a collateral matter, IDA was asked to ascertain whether there was a direct correlation between NASA's implementation of a full-cost-recovery policy and declining use of the three subsonic wind tunnels.

B. Study Objectives

The objectives of the study were as follows:

- identify foreseeable adverse effects of the closure of the subsonic wind tunnels on research and developmental requirements of the military

departments and the U.S. aerospace industry, with particular emphasis on the two large-scale tunnels;

- determine what approaches the DoD might take to prevent those closures;
- identify alternatives that the DoD might take to ameliorate the effects on its test and evaluation requirements in the event that the subsonic wind tunnel test facilities at the Ames Research Center continue to remain unavailable for further use; and
- provide an assessment of the relative merits of those alternatives.

Consideration was to be given to:

- the effectiveness of interagency agreements and “reliance” arrangements in effect between the DoD and NASA at the time of the decision to inactivate the tunnels,
- the effect of NASA’s adoption of a full-cost-recovery policy on use of the affected wind tunnels,
- the apparent trend on the part of the U.S. aerospace industry and the DoD components to increase their dependence on foreign facilities to satisfy subsonic wind tunnel testing requirements, and
- the merits of substituting modeling and simulation for wind tunnel testing.

C. Study Approach

The study team first identified the principal DoD and industry organizations likely to be affected by inactivation of the subsonic wind tunnels at the Ames Research Center, as well as key personnel involved in the decision to close those tunnels. Then we collected data through interviews, site visits, and documentation. Appendix A lists those persons who made principal contributions to our research. Collected documentation included news releases, congressional testimony, utilization records for the two large/full-scale subsonic wind tunnels at the Ames Research Center, financial policies and guidance promulgated by NASA Headquarters regarding full-cost recovery, descriptions of North American and European large-scale subsonic wind tunnels, and interagency agreements with applicability to wind tunnel test facilities that were in effect between the DoD and NASA in the spring of 2003.

Using information from documentation and interviews, we estimated the effect that the closure of the subsonic wind tunnels at the Ames Research Center would have on the DoD and the U.S. aerospace industry. We assessed the efficacy of existing interagency agreements and alliances in the context of the

decision to inactivate the subsonic wind tunnels. Then we explored the reasons for the apparent migration of subsonic testing work from the United States to foreign wind tunnel facilities. In conjunction with those efforts, we evaluated the hypothesis that a cause-and-effect relationship exists between the implementation of NASA's full-cost-recovery policy and declining use of the large/full-scale subsonic wind tunnels at the Ames Research Center, and we identified a number of factors that cumulatively contributed to declining use, and eventual inactivation, of those facilities. Then we derived findings from our analysis and developed a prioritized set of alternative approaches for the DoD's consideration with respect to its future subsonic wind tunnel testing requirements.

D. Organization of the Report

Chapter II of this report describes the historical basis for the respective roles that the DoD and NASA have with respect to wind tunnel test facilities. Chapter III provides an explanation for NASA's recent decision to announce the prospective closure of the National Full-Scale Aerodynamic Complex (NFAC) and the 12-Foot Pressure Wind Tunnel at the Ames Research Center. Chapter IV assesses the effectiveness of existing interagency agreements and organizations in providing for wind tunnel testing requirements of the DoD during the process of deciding to subject the wind tunnels at the Ames Research Center to closure. Chapter V evaluates the question of whether there was a correlation between NASA's adoption of a full-cost-recovery policy and declining use of its subsonic wind tunnels and identifies factors other than full-cost recovery that have contributed to decreased use of those tunnels. Chapter VI addresses the current long-range forecast of testing requirements for the use of NASA's subsonic wind tunnels and contains observations on the forecasting process itself. Chapter VII explains why U.S. aircraft companies, and some DoD components, have elected to use foreign wind tunnel facilities to conduct their testing. Chapter VIII summarizes the effect of the closure of the subsonic wind tunnels at the Ames Research Center on the DoD and the supporting U.S. aerospace industry.

Chapter IX contains (1) recommended funding and/or operating options that might permit the NFAC and the 12-Foot Pressure Wind Tunnel at the Ames Research Center to remain functional and (2) a prioritized set of alternatives available to the Department of Defense to ameliorate the effects of the closure of those facilities in the event that the closures actually materialize, together with the associated advantages and disadvantages of each alternative. Chapter X summarizes the findings, conclusions, and recommendations of the study, and it addresses the larger, long-term significance of the closure of the major subsonic

wind tunnels at the Ames Research Center and NASA's implementation of its full-cost-recovery policy.

Appendix A lists the people in both the public and private sectors who provided primary assistance in this study. Appendix B is a memorandum of agreement between the Department of Defense and NASA for the establishment of the Aeronautics and Astronautics Coordinating Board. Appendix C is a list of selected large-scale wind tunnels with subsonic test capabilities, located in North America and Western Europe, that might be suitable for the conduct of some of the wind tunnel testing required by DoD components or supporting elements of the U.S. aerospace industry. Appendix D is the National Aeronautics Test Alliance (NATA) Interagency Agreement. Appendix E provides Ames Wind Tunnel projected occupancy hours from fiscal year 1997 through 2002. Appendix F is a summary of the results of a failed effort that the Arnold Engineering Development Center made to implement full-cost recovery as reflected in a letter from the center commander to the commander of the Air Force Systems Command. Appendix G is a concept paper establishing a framework for a memorandum of understanding between the United States and the United Kingdom on cooperative test and evaluation.

II. Historical Background

There is a long history of both competition and cooperation between the DoD (to include the individual military services) and NASA with respect to the acquisition and operation of wind tunnels. For the most part, the nature of the competition has produced positive results for the United States.

This chapter begins with a brief historical justification for the construction of the three subsonic tunnels that NASA inactivated in the spring of 2003. Through a discussion of the legislative history behind Public Law 81–415, a single Act with two titles (Title I, The Unitary Tunnel Plan Act of 1949, and Title II, the Air Engineering Development Center Act of 1949), we address the context in which Congress funded aeronautical test facilities after World War II and the respective roles that Congress expected of the DoD, NASA, and private industry. We briefly describe the National Aeronautics and Space Act of 1958 before discussing how both that law and Public Law 81–415 have been implemented and interpreted over the past 50 years. We also address the proposal for a new National Wind Tunnel Complex that was developed in the mid-1990s as well as an initiative by the Congress to provide appropriations for new national wind tunnel facilities.

A. The National Flight Aerodynamics Center and the 12-Foot Pressure Wind Tunnel

Construction of the 40×80 -foot wind tunnel at the Ames Research Center began in 1941, and the tunnel became operational in 1944 [1, p. 34].

[T]he purpose of the tunnel was to examine the takeoff and landing characteristics of aircraft. These two periods of flight are extremely sensitive in terms of lift, drag, and stability.

The test section was large enough to accommodate all but the biggest bombers and transports in existence at the time, with their engines operating. Full-scale tests conducted in the 40×80 -foot tunnel resulted in ostensibly minor improvements to aircraft that proved to be significant [1, p. 34].

For example, after tunnel tests, the Douglas XSBD-2 dive bomber was provided with a modified wing-flap system that lowered landing speeds

from 90 to 84 mph. When landing on carriers, these few miles per hour gave the pilot much better control and...significantly reduced the energy that had to be absorbed by the carrier's aircraft arresting gear.

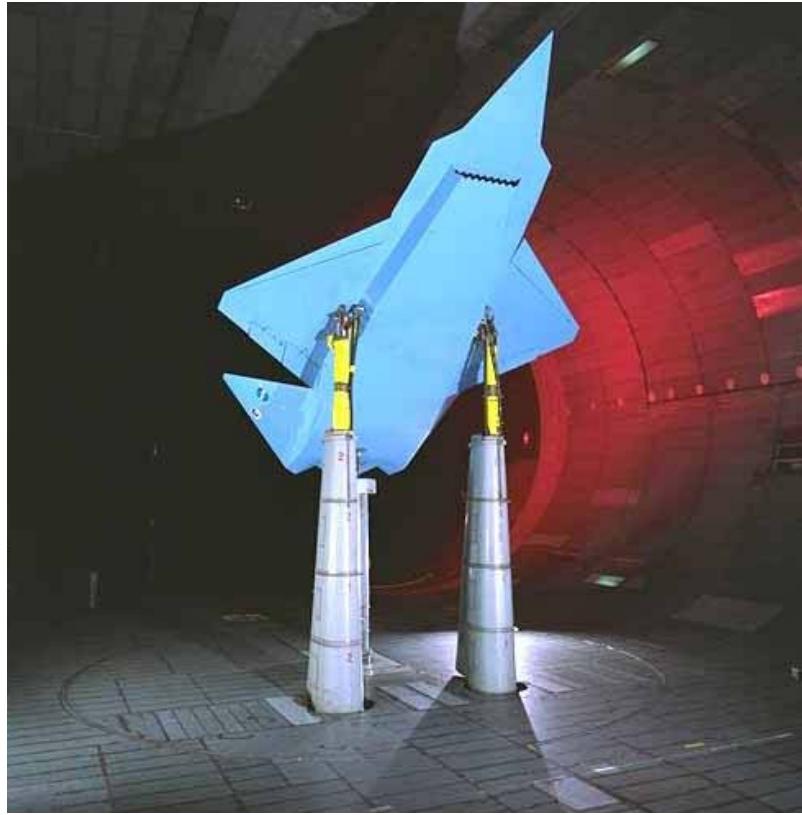
Both test sections in the NFAC have supported aeronautical research and development [2].

The National Full-Scale Aerodynamic Complex (NFAC), 40×80 Foot Wind Tunnel at NASA Ames Research Center is used to support an active research program in aerodynamics, dynamics, model noise, and full-scale aircraft and their components. The aerodynamic characteristics of new configurations are investigated with an emphasis on validating computational methods. Aeromechanical stability boundaries of advanced rotorcraft and rotor-fuselage interactions are explored. Stability and control derivatives are also determined, including the static and dynamic characteristics of new aircraft configurations. The acoustics characteristics of most of the full-scale vehicles are also determined, as well as acoustic research aimed at discovering and reducing aerodynamic sources of noise.... The 40 × 80 Foot Wind Tunnel is primarily used for determining the low- and medium-speed aerodynamic characteristics of high-performance aircraft, rotorcraft, and fixed wing, powered-lift [Vertical/Short Take-Off and Landing] V/STOL aircraft.

The test section measures $40 \times 80 \times 80$ feet, with a 42-inch thick acoustic lining. The tunnel operates in the speed range of zero to 300 knots, and is capable of Reynolds numbers up to 3 million per foot [2]. Figure 1 is a picture of the Subsonic High Alpha Research Concept (SHARC), an Air Force research platform, in the 40×80-foot tunnel.

The 80×120-foot tunnel was added to the 40×80-foot tunnel at the Ames Research Center in 1982. The primary impetus for the substantial new section was the requirement for full-scale testing of Vertical Take-Off and Landing (VTOL) aircraft with a minimum of interference from the tunnel walls [1, p. 135].

To flight test them without wind tunnel trials can lead to disaster, as the history of VTOL flight has repeatedly demonstrated. For example, two U.S. rotary-wing aircraft did bypass full-scale tunnel tests and subsequently crashed during flight testing. One of them encountered technical problems so serious that the \$400 million development program was terminated. In contrast, three other VTOL aircraft did take advantage of the Ames 40×80-foot tunnel. They too failed dramatically at first, but the technical difficulties were resolved in the wind tunnel prior to flight testing, and those craft eventually succeeded.



Source: NASA.

Figure 1. The 40 × 80-Foot Wind Tunnel

The 80×120 -foot test section is the largest in the world. It measures $80 \times 120 \times 190$ feet, with acoustic linings of 8 and 10 inches on the floor and walls, respectively. The tunnel operates in the speed range of zero to 100 knots, and is capable of Reynolds numbers up to 1.1 million per foot. Some of the programs that have been tested in the 80×120 -foot tunnel are the F-18 High-Angle-of-Attack Vehicle, DARPA/Lockheed's X-32, the XV-15 Tilt Rotor, and the Advanced Recovery System Parafoil [3]. Figure 2 shows a UH-60A rotor and an F-18 in the 80×120 -foot tunnel.

The 12-Foot Pressure Wind Tunnel at the Ames Research Center was placed in operation in 1946. It was designed to simultaneously provide high Reynolds numbers, high subsonic speeds, and very low airstream turbulence [1, p. 35]. In fact [4]:

The...12ft Pressure Wind Tunnel...is the only large scale, pressurized, very-low turbulence, subsonic wind tunnel in the United States. It provides unique capabilities in high Reynolds number testing for the development of high-lift systems for commercial transport and military aircraft and for high angle-of-attack testing of maneuvering aircraft.



Source: NASA.

Figure 2. The 80 × 120-Foot Wind Tunnel

The 12-Foot Pressure Wind Tunnel has a test section that is nominally 12 feet in diameter and 18 feet long. It has a velocity that ranges from .05 Mach to .6 Mach, can be pressurized up to 6 atmospheres, and its high Reynolds number is 12 million per foot [4 and 5, p. 107]. According to Baals and Corliss [1, p. 36]:

Perhaps the tunnel's greatest contribution was in the development and testing of wing landing-flap systems at high Reynolds numbers. Almost all our modern military and commercial aircraft have benefited from this research. More recently, the low-turbulence qualities of the tunnel have been exploited in critical laminar-flow-control experiments in the development of fuel-efficient, long-range transports.

Figure 3 shows a scale model of an F-18 in the 12-Foot Pressure Wind Tunnel.



Source: NASA.

Figure 3. The 12-Foot Pressure Wind Tunnel

B. Legislative History Behind Public Law 81–415

Upon exit from World War II, the U.S. technical community became aware that Germany had built and was using testing facilities that simulated the flight environment to produce weapon systems with capabilities well beyond those in the United States.

The House Armed Services Committee recognized this situation in 1949 in its report on S. 1267 [6, pp. 2300–2301].¹

American aeronautical research has been shown to have lagged dangerously behind the German advances in the fields of jet propulsion and high-speed flight prior to and during World War II.... The Congress would be derelict in its duty to provide adequately for the national defense if it failed to recognize that some of the very same conditions which

¹ Section 1267 was entitled “An Act to promote the national defense by authorizing a unitary plan for the construction of transonic and supersonic wind-tunnel facilities and the establishment of an Air Engineering Development Center.” The bill, as amended through the legislative process, became Public Law 81-415 on October 27, 1949 [7].

previously led to our taking second place in the race for more advanced aeronautical weapons may still be present today and that the existence of such conditions can lead to a repetition of our earlier experiences—possibly with far more disastrous consequences.

Although the aeronautical community in the United States was aware of some of these deficiencies, they were unaware of the magnitude of the German advancements. In 1938, General Arnold attempted to develop large engine and aerodynamic test facilities at Wright Field in Dayton, Ohio. Since the Army Air Force farmed out its research and testing to other agencies (primarily the National Advisory Committee for Aeronautics [NACA]),² the General wanted the military to maintain better control over aircraft development. Other agencies (primarily NACA) objected to the proposal and suggested that the facilities be located at NACA sites. The demands of World War II brought the deliberations to a halt.

The House Armed Services Committee's report sheds light on the reasoning behind the congressional response [6, p. 2301].

...nor can the Congress relax in the comfortable assurance that aeronautical research and development are entrusted to the NACA...or to the aeronautical industry which normally develops and produces newer and better types of aircraft, or to the Air Force and Navy upon whom rests the responsibility for the conduct of aerial warfare. It is imperative that the Congress recognize that these very same responsibilities were vested in the identical agencies...prior to and during World War II; yet that fact did not prevent our drifting dangerously far behind the enemy in the more advanced fields of aeronautical research and development....

The U.S. military, the aircraft industry, and the Congress vowed to correct this situation and never again permit the United States to lose its aeronautical preeminence. Through Public Law 81–415, Congress directed and funded the establishment of major ground-based testing resources that included some university wind tunnels, major wind tunnels at existing laboratories (primarily NACA and the Navy), and creation of a new Air Engineering Development Center, which would become the Air Force's Arnold Engineering Development Center (AEDC).

In this context, Congress perceived a need for Federal support of basic research, and the language of the House Armed Services Committee's report provides evidence of that [6, p. 2303].

² NACA was a predecessor to NASA.

The tendency of this country to excel in...applied research and the development of new products and industrial techniques too often overshadows our simultaneous tendency to lag dangerously behind other nations in fundamental or basic research—fields which do not offer the same prospect of immediate financial return on investment and which therefore tend to be neglected.

The committee explained how it perceived NACA's role with respect to industry's need to test models while developing new aircraft and missiles [6, p. 2307].

[I]t is the sense of the committee that ...these facilities, although allocated to NACA on a so-called housekeeping basis and staffed by its personnel, shall be available to satisfy industry's requirements for the testing of experimental models in the course of development of new aircraft and missiles.

Although Public Law 81–415, as originally enacted and later amended, focuses on transonic and supersonic wind tunnel facilities, the legislative history behind the law is significant. The House Armed Services Committee report, which is cited several times here, substantially reflects the Senate report accompanying the same bill. The reports show the context in which the legislation was enacted, and the intent of Congress at that time.

C. Public Law 85–568

The National Aeronautics and Space Act of 1958 enlarged the NACA charter to include space activities, which Congress declared would be “devoted to peaceful purposes for the benefit of all mankind.” The following excerpts from the act affect the discussion to follow [8, Section 102(b)]:

The Congress declares that the general welfare and security of the United States requires that adequate provision be made for aeronautical and space activities. The Congress further declares that such activities shall be the responsibility of, and shall be directed by, a civilian agency exercising control over aeronautical and space activities sponsored by the United States, except that activities peculiar to or primarily associated with the development of weapons systems, military operations, or the defense of the United States (including the research and development necessary to make effective provision for the defense of the United States) shall be the responsibility of, and shall be directed by, the Department of Defense; and that determination as to which agency has responsibility for and direction of any such activity shall be made by the President in conformity with section 201(e).

Section 201(e) establishes the National Aeronautics and Space Council, which advises the President with respect to a number of duties, including [8, Subsections 201(e)(3) through (5)]:

Designate and fix responsibility for the direction of major aeronautical and space activities.

Provide for effective cooperation between NASA and DoD in all such activities, and specify which of such activities may be carried on concurrently by both agencies notwithstanding the assignment of primary responsibility therefore to one or the other of such agencies.

Resolve differences arising among such departments and agencies of the United States with respect to aeronautical and space activities under this Act,....

The act further declares that aeronautical and space activities of the United States involve [8, Section 102(c)(8)]:

[T]he most effective utilization of the scientific and engineering resources of the United States, with close cooperation among all interested agencies of the United States in order to avoid unnecessary duplication of effort, facilities, and equipment.

It goes on to say [8, Section 203(b) (6)]:

In the performance of its functions the [National Aeronautics and Space] Administration is authorized...to use, with their consent, the services, equipment, personnel and facilities of Federal and other agencies with or without reimbursement....Each department and agency of the Federal Government shall cooperate fully with the Administration in making its services, equipment, personnel and facilities available to the Administration, and any such department or agency is authorized, notwithstanding any other provision of law, to transfer to or receive from the Administration, without reimbursement, aeronautical and space vehicles, and supplies and equipment other than administrative supplies or equipment;....

D. Other Considerations

The two referenced statutes have provided a map for cooperation between the DoD and NASA for over 4 decades. During this period, additional testing facilities have been constructed by both agencies, cooperative agreements have evolved, and operational emphases have changed. A review of some of these events will place this report in better perspective.

1. Construction of New Test Facilities

While NASA and the DoD on occasion competed for new test capability, the parties involved assured that there was no duplication of capabilities and that major test capabilities encompassed the requirements of both the military and industry. Thus, the tools needed for design and development of new aircraft reside in both agencies. James Mitchell, a former Chief Scientist at AEDC (and one of the authors of this paper), noted that, in his experience, more wind tunnel hours were provided by NASA than by the DoD in the development of some military aircraft. This is not unexpected, since NASA supplies the low speed and dynamics wind tunnel capability that supplements the DoD's transonic, supersonic, and hypersonic wind tunnel capabilities.

During the late 1960s and early 1970s, the DoD advocated and justified the need for three major test facilities in the United States; a high-Reynolds-number transonic wind tunnel; a low-speed, high-Reynolds-number tunnel; and a high-altitude, high-Mach-number facility to develop aircraft turbine engines. These facility concepts were coordinated with NASA and industry. A series of events resulted in DoD sponsorship of the Aeropropulsion Systems Test Facility at AEDC and NASA sponsorship of the cryogenic National Transonic Facility at NASA Langley. NASA's Ames Research Center contended that the existing 12-Foot Pressure Wind Tunnel adequately satisfied the low-speed, high-Reynolds-number requirement and instead sought and received funds to construct an 80×120 -foot addition to the 40×80 -foot wind tunnel. The construction of the 80×120 -foot tunnel was completed in 1982. By 1986, the 12-Foot Pressure Wind Tunnel became inoperable because of a fault in the pressure shell, and, in the early 1990s, NASA funded its reconstruction, with a reopening in 1995. The type of appropriations provided for that project, and the restrictions on the use of such appropriations, prevented NASA from improving the size and performance of the facility to match some desirable facility capabilities available in England and France.

In 1992, the Boeing Company initiated a search for a site on which to construct major new state-of-the-art transonic and low-speed wind tunnels. The preliminary design showed the cost to construct the new facility to be around \$1.2 billion for a project for which Boeing had allocated \$500 million. The Boeing CEO made the decision to abort the project, believing that the future transport market was not strong enough to support such a large investment by the company.

Following Boeing's decision not to go forward with its plans, a consortium was formed from industry, the DoD, and NASA to explore the feasibility of

developing a national wind tunnel capability consisting of two new state-of-the-art tunnels, one subsonic and one transonic. The project became known as the National Wind Tunnel Complex and preliminary design was funded by Congress. Initial estimates for the two tunnels placed the cost at more than \$2 billion. Subsequently, the scope was reduced to a single tunnel, with a cost estimate of \$1.2 billion.

In 1995, Congress enacted Public Law 103–327, and it provided \$400 million in appropriations to NASA for the construction of new national wind tunnel facilities, subject to the condition that the funding would be rescinded on July 15, 1995 unless the President requested at least \$400 million in the fiscal year 1996 budget for the continuation of the wind tunnel initiative [9]. The appropriation was to cover NASA's share of the \$1.2 billion price tag for the new wind tunnel. The Congressional Conference report (H. Report 103-715) asked the President to submit a comprehensive plan and strategy specifying the anticipated share of the construction costs that would be borne by the private sector as well as the share that would be paid by Federal agencies other than NASA. The latter share was to be based on anticipated usage of the completed facility. However, neither the DoD nor industry was forthcoming with their respective shares, and the project subsequently was put on indefinite hold.

2. Funding for Operational Costs

While this subject is addressed in the National Aeronautics and Space Act of 1958, there have been several iterations that have markedly affected the use and usefulness of the country's test resources. Through the 1950s and 1960s, the test facilities in both the DoD and NASA were operated on "institutional" funding. Institutional funding in this context means that the U.S. Government organization that owned and operated the facilities essentially paid for the maintenance, repair, and operation of those facilities from its own appropriated funds. While government customers were not charged occupancy costs, they often paid for facility equipment and/or minor changes that would benefit their test programs. Commercial customers were charged occupancy costs by direction of Congress, but NASA would often view the test program as additive to their research mission and, thus, void the charges.

In the 1970s, the DoD implemented a charge policy whereby all parties (DoD, NASA, and industry) would reimburse "direct" costs according to a fixed scale. While these were not full costs with overhead, they were sufficient to cause problems for programs that had never paid for testing. Two significant changes occurred. The Air Force laboratories, which had been occupying the wind tunnels about one-third of their time, could not afford to use their own Air Force

test facilities and made arrangements with NASA to use its “free” test facilities for research programs. Also, since the NASA test facilities were free to DoD users, the aircraft development programs used these facilities when possible, sometimes accepting lesser test capability to conserve program funds. In general, the fiscal policies implemented and practiced by the DoD discouraged the use of DoD wind tunnels for both research and aircraft development. There is an incentive to use less expensive, but less capable, test facilities to save a relatively small cost difference in test article and facility operating costs. Consequently, design anomalies sometimes show up on flight aircraft, which could, and should, have been exposed and resolved in wind tunnel testing.

In today’s environment, an emphasis on space activities and budget constraints has led NASA to reduce the emphasis on the aeronautics role that was established in Public Law 81–415. By 1999, personnel at NASA’s Ames Research Center had become concerned about the effect of this change in priorities [10, p. 3]:

The change away from a philanthropic model that supports the aeronautics industry with large amounts of research and development dollars has been forced by significant budget cuts and a generally lower priority being put upon the aeronautics enterprise within NASA....Presently, NASA wishes to be certain that the current R&D [Research and Development] testing capability will remain available to the aeronautics industry even in low demand years. This decision requires a minimum level of funding to ensure that reasonable testing capability remains intact. We are concerned, however, that this level of support may lose favor with NASA headquarters in the future.

Now, NASA has announced the closure of unique national test capabilities and full-cost recovery for other aeronautical test facilities. The likely outcome will be closure of additional test facilities. With full-cost recovery in NASA test facilities, it will be difficult for both NASA and DoD-sponsored aeronautics research activities to find affordable test facilities. Even well-funded aircraft development programs may not be able to react to the increased cost of testing, and they will seek other (often inadequate) alternatives or increase development risk by not testing at all.

For 5 decades, the United States has been the aeronautics power, the producers of the best aircraft, and the world’s major supplier of military and commercial aircraft. The backbone of this success was provided by the NASA and DoD aeronautical test facilities that began with Public Law 81–415, and a substantial investment of public funds. The country maintained leadership in military aeronautics and its commercial aircraft industry became a major engine

in the U.S. economy, with a sizeable export market. However, the United States is now nearing full-circle since the 1940s, and it is poised to lose its global aerospace technological superiority and return to its World War II status.

III. Why Is NASA Closing the Wind Tunnels at the Ames Research Center?

Multiple factors were responsible for NASA's decision to mothball the National Full-Scale Aerodynamic Complex and the 12-Foot Pressure Wind Tunnel at the Ames Research Center and announce its plans to close those facilities permanently if sufficient workload does not materialize by the end of fiscal year 2004.

A. Recent Announcements

In an announcement published in *The Mercury News* on May 17, 2003 [11], NASA officials promulgated the decision to close the NFAC and the 12-Foot Pressure Wind Tunnel at the Ames Research Center. The announcement disclosed that the facilities could very well be mothballed forever. It went on to state that the closures would be permanent if no major contracts from the Department of Defense or the private sector materialized before the end of fiscal year 2004.

A subsequent NASA release, which appeared on the Web site SpaceRef.com on June 6, 2003 [12], explained that the two facilities were not generating sufficient testing income in fiscal years 2002 and 2003 to pay for their operating costs. The release, which was a memo from the Acting Director, Research and Development Services, at the Ames Research Center, said that since the May 2003 announcement that the tunnels were being closed, several customers with unscheduled testing requirements had expressed their concerns over the NASA decision to both the Ames Research Center and the NASA Headquarters. Between the public announcements and interviews with NASA personnel conducted for purposes of this report, we were able to identify the factors that led NASA to close the wind tunnel facilities.

B. Rationale for Closure of the Tunnels

The tunnels are being closed because several conditions converged in a manner that led to underutilization of the facilities. There have been fewer new starts in

aircraft development than has been the case in recent history. The U.S. rotorcraft industry, for instance, has experienced no “new starts” in the past 13 years [13].³ The number of defense contracts involving large/full-scale wind tunnel testing work has declined. The number of defense contractors has decreased through corporate mergers and consolidations, and several of them began using alternative facilities for their wind tunnel testing work. Some DoD components and U.S. aerospace companies have decided to take their wind tunnel testing work to alternate facilities outside the United States, and they continue to do so. The reasons for those decisions are discussed in Chapter VII. Advances in computational fluid dynamics have obviated the need for some early-design wind tunnel testing, yet overall design dependency on wind tunnel data remains strong.

In addition to the foregoing, U.S. Government investment in aeronautical research has declined. An article that appeared in *Aviation International News* in July 2001 pointed out that, whereas aeronautics accounted for \$1 billion worth of the NASA budget in 1994, it had fallen to \$380 million by 2001 [14]. Similarly, Department of Defense spending for aircraft research, development, testing and evaluation was reduced significantly in the 1990s [15, p. 6–8].

The Army and NASA have historically jointly funded a program for rotorcraft research. Under the terms of an agreement that dates back to 1965, the Army and NASA have contributed funding to rotorcraft research on an equal basis [16]. Bell, Boeing, and Sikorsky provided additional funds [17]. However, beginning with fiscal year 2002, NASA has tried to eliminate funding for rotorcraft research and technology from its budget. Although various stopgap measures have been proposed to continue or replace NASA’s share of the funding for rotorcraft research and development, the Army does not have the resources to replace the NASA share, jeopardizing continued rotorcraft research and development testing at NASA’s centers. Through its Vehicle Systems Technology program, NASA is funding \$15 million in rotorcraft research in fiscal year 2004 and coordinating that investment with the Department of Defense.⁴

³ In congressional testimony, M. E. Rhett Flater actually said that there were no new starts in the past 15 years. However, he advised us that, due to the fact that the “downselect” on the Comanche took place in 1991 (although it was based on a request for proposal that was generated in the 1980s), any misunderstanding could be avoided by simply stating that it had been 13 years, vice 15, without a new start in the U.S. rotorcraft industry.

⁴ In its fiscal year 2002 budget, NASA did not request any funds in the rotorcraft research budget line item. Nevertheless, Congress earmarked \$12.5 million for that purpose in fiscal year 2002. While this report was being prepared for public release, NASA provided input that indicated \$15 million within its overall Vehicle Systems Technology line item was

The problem resulting from NASA's recent elimination of the rotorcraft research line item from its budgets has been exacerbated by the Office of Management and Budget's challenge to NASA's plans to pursue rotorcraft development in the future. The Office of Management and Budget (OMB) position is reflected in a letter from the OMB Deputy Associate Director, Energy, Science, and Water Division, to the NASA Comptroller, dated April 14, 2003. An extract from that letter serves to illustrate OMB's position with respect to NASA's role in any defense-related rotorcraft research [18].⁵

[W]e understand that NASA may pursue rotorcraft research in a future operating plan. You should know that we planned to oppose the rotorcraft funding and will likely do so in the future....We do not support redirecting limited civil aeronautics research dollars to activities that primarily support military needs. As a general rule, OMB encourages responsible departments and agencies to pay for the full cost of their activities, including the cost of using the technical resources of another department or agency. NASA expertise should be made available to the military when necessary, but the Defense Department should pay for those capabilities when it is using them.

Concurrently, NASA has been trying to implement full-cost accounting and a full-cost-recovery policy. As that effort moved toward full implementation, customer costs for the use of wind tunnels increased as the NASA centers identified various components of the fully burdened cost of operations and added them to customer rates. This policy contributed to at least two decisions to move major test programs out of the NFAC (Army rotorcraft testing and the

allocated in fiscal years 2003 and 2004 for rotorcraft research, and NASA appears prepared to continue to do so in coordination with the DoD rotorcraft research program.

⁵ Several provisions of NASA's 2003 Strategic Plan are noteworthy here. "NASA is the Nation's leading organization for research and development in aeronautics and space. We have developed expertise, tools, and facilities that collectively represent a unique national asset. It is our mandate to undertake challenging projects of national importance that fit our unique capabilities" [19, p. 11]. "NASA works collaboratively with the Department of Defense to develop technologies and systems that help to keep U.S. military aviation and space capabilities the most advanced in the world" [19, p. 16]. "By developing and transferring technologies, NASA's investments in Aeronautics Technology play a key role in...increasing performance of military aircraft..." [19, Appendix A, p. A-7]. "NASA will support national security by working with DoD through research collaborations...arising new threats call for innovation in...subsonic and supersonic aircraft" [19, Appendix A, p. A-10]. On the other hand: "Future changes in law and policy may invalidate or reinforce goals. Administration and congressional budget decisions also affect NASA's ability to meet the goals and objectives as set forth in this plan" [19, Appendix A, p. A-22].

Joint Strike Fighter). With respect to Army rotorcraft testing, the major reason for withdrawal was NASA's curtailment of its contribution to the rotorcraft research, exacerbated by the institution of full-cost recovery and the closure of the NFAC. In the case of the JSF, the program was given a full-cost-recovery price to allow the testing to proceed. That price was prohibitive, and the JSF Program Office made the decision to withdraw and accept the technical challenges of moving the test overseas to the DNW wind tunnel. An additional factor in the decision was the fact that the NFAC was expected to close after the JSF entry was completed, leaving the JSF program in a difficult situation should technical problems of any kind warrant a return to the facility for subsequent testing. Therefore, one can attribute the withdrawal to the implementation of NASA's full-cost-recovery policy, exacerbated by (1) the withdrawal of other programs causing overhead costs normally spread among users to be assigned to the JSF entry alone and (2) the planned subsequent closure of the facility.⁶

Under the circumstances, NASA officials have concluded that the facilities must be closed.

C. Two Observations on the Closures

A recent study by the National Research Council provides a different perspective on the applicability of utilization rates to decisions to close aeronautical test facilities [20, p. 35]:

The amount of testing at a particular facility is generally used as a basis for deciding whether to continue to maintain the facility in an operational status. However, past use is not a good predictor of future need. Very little testing has been done in some...facilities in the past three years. However, the decision to mothball or decommission these facilities should be based on the need for their capabilities in the future.

We found that the decision to close the tunnels appears to be inconsistent with the "Financial Management" portion of NASA's 2003 Strategic Plan, which reads, in pertinent part [19, Appendix I, Section IS-1, p. A-1]:

⁶ Our documented sources for the information regarding Army rotorcraft testing include multiple interviews with Andrew W. Kerr, Chief of the Army's Aeroflightdynamics Directorate at the NASA Ames Research Center; M. E. Rhett Flater, Executive Director of the American Helicopter Society International; and various personnel during meetings conducted at the NASA Ames Research Center and the Naval Air Systems Command. Source of the JSF comments included Kerr, personnel at the Ames Research Center and the Naval Air Systems Command, and two Lockheed Martin officials.

NASA is responsible for complex and high-value systems such as...wind tunnels...that are unique in the world. These activities represent large investments by the American public.

D. Conclusions

NASA's decision to mothball the NFAC and the 12-Foot Pressure Wind Tunnel at the Ames Research Center was the result of multiple factors. In essence, all of the following factors contributed to the closure of the tunnels:

- the decline in aeronautical research in the United States,
- the lack of new aircraft development programs,
- the migration of some wind tunnel testing work to alternate test facilities (including those in foreign countries),
- the decision to curtail NASA funding for rotorcraft research and development, and
- the implementation of full-cost accounting and full-cost recovery

Cumulatively, these causal factors created a situation in which the subsonic wind tunnels at Ames Research Center cannot be expected to generate enough workload at fully burdened rates to operate on a self-sustaining basis.

IV. Interagency Organizations and Agreements

This chapter examines the organizations and agreements in place between NASA and the DoD at the time NASA initiated actions leading to the closure of the subsonic wind tunnels at the Ames Research Center. It also examines the commitments and responsibilities of the parties under those agreements. In this context, it is important to bear in mind that the DoD has traditionally not invested in subsonic wind tunnels, but has instead relied on NASA for all its subsonic wind tunnel testing requirements [21, p. 4, fn 8; 22, p. 47].

A. Aeronautics and Astronautics Coordinating Board

The Aeronautics and Astronautics Coordinating Board (AACB) was formed to establish coordination between NASA and the DoD because of the interfaces of the two agencies' missions created with the formation of NASA.

Present-day NASA was established by the U. S. Congress with the passage of the National Aeronautics and Space Act of 1958 [8]. NASA was designated the civilian agency responsible for all aeronautics and space activities except for those peculiar to, or primarily associated with, the development of weapon systems, military operations, or the defense of the United States, which would be left to the DoD. The act directed that the aeronautical and space activities of the United States be conducted so as to contribute materially to "the most effective utilization of the scientific and engineering resources of the United States, with close cooperation among all interested agencies of the United States in order to avoid unnecessary duplication of effort, facilities, and equipment." Interdependence was implied in the statutory language, but not explicitly provided for.

The act created a Civilian-Military Liaison Committee (CMLC) to provide a mechanism for NASA and the DoD to advise and consult with each other on all matters within their respective jurisdictions relating to matters covered by the Act. The parties were directed to keep each other fully and currently informed.

The AACB was instituted by the DoD and NASA in September 1960 to replace the CMLC for coordination of the aeronautical and space activities of the DoD and NASA at all management and technical levels. Its status was formalized in 1965 when then-President Lyndon Johnson abolished the CMLC

and established the AACB in a Reorganization Plan submitted to Congress, according to a history of the NASA Office of Defense Affairs prepared by Admiral W. F. Boone [23, p. 37]. Appendix B contains a copy of the current Memorandum of Agreement between NASA and the DoD.

Admiral Boone's history also revealed that the AACB established a Joint Annual Facilities Review that was effective in that "each year it eliminated a certain amount of construction which, if approved, would have constituted unjustified duplication," and "served to reassure the Bureau of the Budget and the Congress that NASA and the DoD were effectively working together to make the maximum utilization of existing government facilities to accomplish [Research and Development] R&D work" [23, p. 41]. This process was apparently continued for many years before being dropped as an annual AACB activity. We found evidence that there is an annual facility review process still going on, but the AACB does not oversee it. The annual facilities review focused on new investments and would not have included plans to deactivate facilities, reduce funding levels, or change financial policies.

There was no indication that the AACB was involved in the decision to inactivate the three wind tunnels at the Ames Research Center. The last documented activity of the AACB was its DoD/NASA Cooperation Initiative of 1995–1996. The activity involved the review and recommendations of seven Integrated Product Teams (IPTs) in areas of mutual technical and operational interest. The IPT recommendations are documented in a final report issued in May 1996 [24]. One of the recommendations was to establish alliances in six major facilities areas. Recent discussions with knowledgeable personnel indicate that there has been no AACB activity in the last 5 years.

B. National Aeronautical Test Alliance

In order to discuss the National Aeronautical Test Alliance (NATA), it is necessary to first examine the NASA-DoD Major Facilities Alliances that were created as a result of the AACB initiative of the mid-1990s and in which NATA has its origins. By January 1998, NASA and the DoD had negotiated and signed agreements formally establishing six cooperative alliances related to test facilities. Two of these were the National Wind Tunnel Alliance (NWTA) and the Air Breathing Propulsion Test Facilities Alliance (ABPTFA).

Separate Memoranda of Agreement (MOA) between NASA and the DoD formalized the NWTA and ABPTFA [25]. Under the agreements, the Administrator of NASA and the Secretary of Defense agreed to identify, study

and implement cost-saving efficiencies between NASA and the DoD. For example, among the responsibilities of the NWTA were the following:

- identifying any areas of reliance between the two agencies;
- developing a test capability map, master plan and investment strategy to efficiently meet national needs and avoid unwarranted duplication;
- reviewing significant facility modifications, upgrades, and new construction; and
- making recommendations to ensure alignment with the master plan and investment strategy.

The ABPTFA agreement contained similar provisions. Of particular significance to the present study, each agency was to provide for continuing support for facilities on which the other agency had agreed to rely—such a facility would not be closed or diminished in capability without prior coordination between the agencies. The alliance was to address events that affected interagency reliance on a case-by-case basis. Both the NWTA and the ABPTFA agreements contained this provision.

The annex to the MOA for the NWTA contained additional provisions explicitly addressing the DoD's dependence on NASA's subsonic wind tunnels (with the NWTA providing oversight for assuring that DoD long-range subsonic wind tunnel test requirements were provided to NASA) and assessing NASA plans for closing, operating, and modifying its subsonic wind tunnels relative to satisfying DoD requirements. Among the deliverables prescribed by the NWTA annex were DoD subsonic test requirements to NASA and NASA plans for their subsonic wind tunnels to the DoD.

There appear to be sufficient provisions within the two alliances to have established proper coordination between NASA and the DoD on NASA's decision to close its low-speed wind tunnels, had they been active. However, according to David Bond, Deputy Director for Operations at Air Force Materiel Command, the NWTA and the ABPTFA were superseded by a subsequent alliance, the National Aeronautical Test Alliance (NATA), and the original agreements are no longer active.⁷ While the NATA MOA does not state that NATA supersedes the NWTA and the ABPTFA, that seems to have been the intent, and their respective MOAs have since been allowed to expire.

⁷ David Bond serves as the DoD Director for NATA.

Like the NWTA and the ABPTFA, the NATA was formed by an interagency agreement between NASA and the DoD [26]. Its purpose is to facilitate the establishment of an integrated national strategy for management of NASA and DoD aeronautical test facilities. NATA was established in response to growing concerns over European wind tunnel superiority to U.S. facilities and increasing use of those facilities by U.S. commercial and military aircraft developers. NASA and the DoD determined that the NWTA and ABPTFA should be expanded to address these new concerns, which included facilities access and data security. The NATA agreement also addressed the original objectives of the earlier alliances, although the NATA objectives are stated somewhat differently than those of the NWTA and the ABPTFA. The NATA agreement contains no language that explicitly refers to facility reliance between the agencies, but its requirement for an integrated national strategy for management of aeronautical test facilities certainly implies it. One may infer from the language of the agreement that NATA would have provided an appropriate forum for coordination of NASA's actions with the DoD if they had chosen to use it.

C. Effectiveness of Interagency Organizations and Agreements

Two agreements currently in effect between NASA and the DoD, the ones involving the AACB and the NATA, bear on low-speed wind tunnels, and each agreement establishes an organization or functioning body through which its purpose is to be achieved. In each case, there is sufficient emphasis on the mutual reliance or interdependence of NASA and the DoD on each other's facilities and those of the private sector to expect that major decisions affecting these relationships would be properly coordinated and vetted before implementation – if the agreements are being followed. Unfortunately, the acknowledgement of mutual interdependence and the requirement for coordination explicitly called out in the NWTA MOA was only implicit in the language of the NATA agreement. The intent was there nonetheless.

Considering the two agreements now in effect, and provisions for functioning bodies thereto, and the now-defunct agreements for the CMLC and NWTA/ABPTFA, the question arises as to whether each might have been established because one or more of the others was not accomplishing its intended purpose. It is clear that, while the authors of the MOAs had the foresight to anticipate possible pressures to close facilities critical to the interdependency of essential NASA and DoD operations, neither of the alliances achieved the necessary coordination, and NASA proceeded unilaterally to deactivate

important national capabilities without formal advance notification to the affected DoD components.⁸

⁸ In commenting on these interagency arrangements and agreements in general, Thomas P. Christie, the DoD Director, Operational Test and Evaluation, stated [27]:

Our experience with these arrangements varies considerably.... However, when significant resources are involved, the interagency agreements are too weak to overcome the various institutional pressures. Agency cultures, budget constraints, and local priorities tend to undermine the agreements.

V. Full-Cost Recovery and Declining Utilization

This chapter addresses declining wind tunnel utilization, NASA's full-cost-recovery initiative, and the possible relationship between them. It highlights some reservations about NASA's full-cost-recovery policy, summarizes the results of an Air Force experiment with such a policy, and identifies multiple factors responsible for declining use of the NFAC and the 12-Foot Pressure Wind Tunnel at the Ames Research Center.

A. Utilization Rates

Records verified by the Ames Research Center depict use of the 80×120 -foot and 40×80 -foot wind tunnels at the Ames Research Center over the period from fiscal year 1997 until the time that NASA announced the inactivation of the test facilities in fiscal year 2003. That data is reflected in Table 1.⁹

**Table 1. Wind Tunnel Usage Rates (Hours),
FY 1997–FY 2003**

Fiscal Year	80 × 120-ft. Tunnel	40 × 80-ft. Tunnel
1997	606	0
1998	767	141
1999	1,468	1,273
2000	901	598
2001	1,678	917
2002	595	231
2003	61	363

Source: AEDC provided, and Ames Research Center validated, usage data.

Note: We prorated hours of usage in cases where testing spanned fiscal years.

⁹ Based on the circumstances in effect at the time of writing, we project that the fiscal year 2004 usage rates for both tunnels will be zero. We also recognize that usage rates displayed in this chart are different from those reported by the NASA Inspector General in the table in Appendix E. However, the general trends from both sets of data are the same, and both sets were either provided or approved by the Deputy Wind Tunnel Manager at the Ames Research Center, who was not available to explain the differences at the time this study was prepared. The small differences in data sets do not affect the observations and conclusions in this study.

Although the annual hourly usage rates identified in Table 1 do not reflect a consistent downward trend over the past 5 fiscal years, they clearly show that customer usage of the 2 large-scale subsonic wind tunnels fell off in the last 2 fiscal years.¹⁰

B. NASA's Full-Cost Initiative

NASA began its full-cost initiative in April 1995. However, because of the complexity of the changes that were required to NASA's financial management and the significant difference that the new initiative represented from NASA's historical practices, full-cost management was implemented in phases. Full implementation began on October 1, 2003, the beginning of fiscal year 2004. During the phased implementation period, NASA headquarters kept the various centers apprised of the status of the initiative and provided guidance.

On September 24, 1997, the director of NASA's Financial Management Division issued a memorandum explaining the process of including the agency's overhead rate in calculating full costs for agreements for the provision of goods and services to customer agencies that were either negotiated or signed after October 1, 1997. One section of that memorandum, entitled "Cost Principles," provided a clear picture of how comprehensive the full-cost-recovery policy was going to be. The following words preceded an enumeration of the various types of costs that should be charged [29]:

All new customer orders, including those under amended reimbursable customer agreements will recover full cost, except for written, legally permissible exceptions made by the [Center Chief Financial Officer] CCFO or the Director, Financial Management Division.... Full costs will be charged to the extent they can be reasonably determined, whether from the accounting system or through cost finding. Cost finding includes any reasonable technique for identifying costs that are not directly available in the NASA cost accounting system.

NASA published a "Full Cost Initiative Agencywide Implementation Guide" in February 1999 [30]. The NASA Administrator issued NASA Policy Directive (NPD) 9080.1E, with an effective date of April 27, 1999, addressing

¹⁰ In performing an audit on wind tunnel utilization [28], Howard Kwok of the NASA Inspector General's Office asked the Ames Research Tunnel's Deputy Wind Tunnel Manager to explain the sharp decrease in the use of the NFAC in fiscal year 2002 compared to fiscal year 2001. The Deputy Wind Tunnel Manager's response was that in fiscal year 2001, the rotorcraft program "purchased the whole complex to run tests in both sections," and that in fiscal year 2002, there was basically no rotorcraft program or funds for such testing.

review, approval, and imposition of user charges. That policy directive covered services provided to customers outside the Federal Government and stated that charges shall be imposed to recover at least the full cost to the Federal Government of providing that service, covering the direct costs and indirect costs of carrying out that activity, including the salaries and benefits of the employees involved; the maintenance, operation, and depreciation of buildings and equipment; and a proportionate share of NASA's management and supervisory costs. The directive also recognized that statutes, executive orders, or the Office of Management and Budget may allow exceptions to full-cost recovery; and it provided the NASA Center directors with a mechanism to recommend, and obtain approval for, exceptions to the imposition of user charges [31].

Chapter 9090 of the NASA Financial Management Manual contains policies applicable to customer agreements, whether reimbursable or not. The basic full-cost-recovery policy reflected in paragraph 9091.1b is that non-Federal customers will be charged full cost "except where less than full cost pricing is required" and other Federal agencies will be charged full cost, "except for depreciation, pension costs funded by the Office of Personnel Management, and any other costs not reimbursables [sic] to current NASA appropriations." Section 9091-4 of the Manual provides that non-Federal customers will be billed, and pay, in advance for services provided under reimbursable agreements and reimbursable orders. It provides that reimbursable work for both Federal and non-Federal customers will not be initiated in the absence of either a signed agreement or before such time as reimbursable budgetary resources are available [32].

The NASA "Full Cost Initiative Agencywide Implementation Guide" categorizes wind tunnels as service facilities. The guide provides that the basis for assigning the costs of wind tunnel services should be direct labor hours. It characterizes such services as labor intensive, and stipulates that, "where possible, service activity labor should be charged directly to benefiting projects or G&A [General and Administrative]." It states that work orders are another acceptable basis for the assignment of service pool costs if the work orders are consistently based on full costs.

It is noteworthy that Appendix 2 of the NASA "Full Cost Initiative Agencywide Implementation Guide" explains that a team of NASA's financial and program managers consulted with representatives of industry and other Federal organizations during the development of the full-cost initiative. Some of the organizations consulted, as early as 1995, include Boeing, Lockheed Martin, the Army Materiel Command, the Naval Air Warfare Center's Weapons Division at China Lake, and Edwards Air Force Base.

C. Reservations about Full-Cost Recovery

During interviews for this study, personnel in NASA, the DoD, the aerospace industry, and industry associations expressed reservations about NASA's full-cost-recovery policy in the context of the need for wind tunnel test facilities in the United States. Such reservations included the contention that full-cost recovery for Government projects conducted by industry with Government support, is contrary to Title 14 of the Code of Federal Regulations. Chapter V, Part 1210, concerns development work for industry in NASA tunnels. Section 1210.2(b) reads as follows [33]:

Government projects. Includes work for industry on projects which are either under contract with or supported by a letter of intent from a Government agency. The work must be requested by the Government agency. No fee will be charged for Government projects.

This issue is discussed further in Section A.2 of Chapter X.

In addition, paragraph 9091-2 (a) (6) of the NASA Financial Management Manual provides that, for agreements made under the Unitary Wind Tunnel Act of 1949, "NASA does not charge other Federal agencies or charge depreciation or overhead to non-Federal agencies" [32].

One representative of a major aerospace company, who acknowledged being among those who were consulted when NASA was exploring the full-cost-recovery policy, opined that, if NASA tunnels are operated as "national asset" research facilities (as several persons we contacted recommended), full-cost recovery would be inconsistent with the mission. However, if the intent is to operate the NASA tunnels in direct competition with production tunnels found in industry, the full-cost-recovery business model would be appropriate.¹¹

D. Lessons from the Air Force Experiment in Full-Cost Recovery

According to a 1971 AEDC presentation [34] the AEDC history office provided to us, AEDC began testing the service-funding concept (full-cost recovery) at the outset of fiscal year 1969. During that year, all appropriated funds for testing Air Force systems were provided directly to AEDC. In the following year, former AEDC funds were placed in customer program offices, but with a guarantee that the funds would be spent at AEDC. Each of these

¹¹ E-mail message from Conrad A. Ball, Director, Laboratories and Test Technologies, Boeing Company, to Terrence Trepal, November 10, 2003.

approaches worked satisfactorily from a financial point of view. Although a deficit occurred each year, it was modest. In fiscal year 1971, all guarantees were removed, and AEDC became a competitor in the open marketplace. During that year, a substantial deficit occurred.

Brigadier General Jessup D. Lowe, AEDC Commander, in a letter to the Commander of Air Force Systems Command (AFSC), provides a detailed record of what happened in the AEDC funding experiment. Brigadier General Lowe's letter is provided as Appendix F. A summary of the experience follows.

Fiscal year 1970 ended with a surge of testing that required round-the-clock operations. The problem year, fiscal year 1971, began with a carryover deficit (from the two previous years) of \$1.361 million, which was later funded to AEDC by AFSC. That year, the inadequacies of research, development, test, and evaluation workload forecasting became very visible, presumably because all revenues were to be earned from customers, with no guarantees that they would use AEDC services. Uncertainties in workload led to much difficulty in sizing the AEDC contract, nominally valued at that time at about \$57 million. Ultimately, a decision was made to contract at the minimum level of effort to maintain a viable capability, about \$5 million above the best estimate that could be made of actual workload. Even this level resulted in reductions of 12 percent of contractor workforce and 10 percent of Air Force staff and an increase of 13 percent in prices necessitated by having to spread large fixed costs over a smaller operating workload base.

During the course of the year, the projected \$5 million deficit grew into approximately \$13.5 million with the continued loss of workload. All but \$629,000 of this was paid from funds provided by AFSC headquarters. Brigadier General Lowe, in his closing statements, observed that had AFSC Headquarters not provided their financial support, "we'd have had little choice but to essentially wipe out a national capability that has taken since 1949 to build."

The failed attempt to place AEDC on a full-cost-recovery system was one of the factors that led to the DoD's adoption of the partial reimbursable funding system that now exists within the Major Range and Test Facilities Base (MRTFB).¹² Brigadier General Lowe acknowledged that AEDC's finances could be successfully managed under the 60/40 appropriated/customer funding split

¹² Under that policy, DoD customers are charged for the direct costs of using its wind tunnel facilities, while non-DoD Federal customers and defense contractors are charged direct costs plus an appropriate amount of indirect costs.

achieved in fiscal year 1972, although he suggested that a 75/25 split would be better.

Careful reading of the documents referenced above or provided in Appendix F along with information provided elsewhere in this chapter shows that factors other than full-cost recovery contributed to the drop in workload at AEDC during the experiment. A paper on the feasibility of converting AEDC to an industrial fund activity, prepared in the context of DoD pressure to place MRTFB activities in a full-cost-recovery mode under the Defense Business Operating Fund (DBOF) [35], allows that test customers were not given time to prepare for the dramatic change in test requirements (even though AEDC funds were transferred to customer accounts). Acknowledging that short reaction time could have been a factor, the paper reports that program offices elected to take tests to “free” sites (NASA), lower cost sites (industry sites with testing costs hidden in program costs), or did not test at all. “Test decisions were often made based on near-term cost considerations with little regard to the increased program risks they were incurring.” Nevertheless, in the case of AEDC, final implementation of full-cost recovery in a free market immediately preceded workload reductions so significant as to preclude continued operations under the policy.¹³ This evidence suggests that full-cost recovery can be a strong factor in loss of test workload in Government facilities. It also shows that full-cost recovery creates the incentive for less-than-optimal decisionmaking on the part of program managers.

Upon revision of the funding policy in fiscal year 1972 to provide appropriated funds to cover 60 percent of the cost of providing the capability, lost workload began to return to AEDC.

Long-term effects of the full-cost-recovery experiment at AEDC included damaged relations with many program offices and other activities, as their programs were taxed in order for AFSC to bail AEDC out of the financial deficit of fiscal year 1971. For this and other, mostly financial, reasons many programs continued to use NASA and industry test sites, even after the rescission of full-cost recovery. The Air Force found it necessary to require its program offices to use organic test facilities or to secure a waiver allowing them to test Air Force systems elsewhere, a position that further strained working relationships between AEDC, its test customers, and NASA test centers. Air Force laboratories

¹³ Similarly, in 2003, as NASA’s Ames Research Center was in the final stages of implementing full-cost recovery, the high cost of wind tunnel testing caused the Joint Strike Fighter Program Office to withdraw its test from the NFAC, and operation of the facility could not continue.

for the most part became financially unable to use AEDC test facilities, a condition that remains today even under partial institutional funding. Apart from the workload and cost effects and damaged working relationships already discussed, reference [36] lists effects internal to AEDC as erosion of test and evaluation capabilities, including:

- loss of skilled people,
- loss of independent analysis and evaluation capability,
- decrease on investments for the future, and
- reduced facility readiness through loss of maintenance.

Brigadier General Lowe's concluding paragraph summarizes his view of the funding scenario and explains its lack of success. The paragraph is repeated here for emphasis:

In conclusion, I have not yet, nor do I foresee, becoming an advocate of service funding—particularly in the test and evaluation domain. Increasing complexity of modern aerospace systems demands more and more test and evaluation and exact needs are often most difficult to define or accurately forecast. Many never can be defined in time to match lengthy budgeting, appropriation, and apportionment cycles. Accordingly, I urge that test and evaluation capability be made readily and freely available to whomever and whenever it is needed with accounting for actual program costs as necessary after the fact rather than before. I sincerely feel that this, along with a closer working communion among our researchers, developers, and testers is in the national interests and one of the key answers to better operational systems of the future.

E. Causes of Declining Utilization

As the Cold War ended, there was a downturn in DoD programs, causing the number of DoD programs that use wind tunnels for testing to decline in recent years.¹⁴ Both commercial and DoD aircraft development programs have been “downsized,”¹⁵ and there is currently a great deal of emphasis on cost

¹⁴ The Committee on the Future of the U.S. Aerospace Infrastructure and Aerospace Engineering Disciplines to Meet the Needs of the Air Force and the Department of Defense concluded that “[t]he use of the nation’s wind tunnels has declined significantly” [20, p. 34].

¹⁵ According to the Commission on the Future of the United States Aerospace Industry’s Interim Report #3, dated June 26, 2002, “Over the past 50 years, the number of military manned aircraft design programs per decade has dropped 96% (1950s – 46 programs; 1960s – 16; 1970s – 12; 1980s – 7; 1990s – 6; 2000s – 2...” [15, p. B-48].

during program development. In NASA, (particularly at Ames Research Center), computational fluid dynamics methods have also been consuming resources that might otherwise have been used for ground testing.

Aging facilities and downtimes for renovations have been a factor responsible for the migration of workload from domestic to foreign facilities. The 12-Foot Pressure Wind Tunnel at NASA's Ames Research Center was torn down for renovation in the 1986–1987 time frame, had not been capable of full pressure operation for several years prior, and was not available for testing again until 1995 [37]. The NFAC, consisting of the 80×120 -foot and 40×80 -foot subsonic tunnels, was down for acoustical renovation and motor work for about 4 years from 1995 to 1998.¹⁶ During the time the NASA wind tunnels were closed for renovation, customers found it necessary to take their wind tunnel testing work to alternate facilities.

Boeing's use of the 12-Foot Pressure Wind Tunnel at the Ames Research Center provides an illustration of what transpired. When NASA closed the tunnel for renovation, Boeing made several recommendations for the design of the replacement tunnel, based on experience using the 5-Meter Low Speed Tunnel at Farnborough, England. Boeing's primary concerns had to do with the size and cross-sectional shape of the 12-Foot Pressure Wind Tunnel's test section.

Boeing wanted the test section size increased to be compatible with models developed for the 5-meter tunnel. The smaller cross-section of the 12-foot tunnel required a smaller model to be tested at higher pressure to provide the same Reynolds number as the 5-meter tunnel. Boeing thought this procedure was unacceptable because of its investment in models for the 5-meter tunnel and, more importantly, because smaller models tested at higher pressures in flap-down configurations often suffered from degraded model fidelity (accurate representation of the full-scale aircraft). This deficiency in model fidelity arises because of the excessively large structural parts required to position the flaps at high test pressures, leading to erroneous and generally uncorrectable aerodynamic results. Therefore, as one Boeing official put it, the 12-Foot Pressure Wind Tunnel with its six-atmosphere pressure capability may come closer to approximating flight conditions, but it caused a loss of model fidelity. The effect

¹⁶ Table 1 reflects hours of usage in the NFAC in 1997 and 1998, while this statement indicates that it was closed during 1997 and reopened sometime in 1998. The Assistant Wind Tunnel Manager at the Ames Research Center has indicated that both the statement and the table are correct, and that there is an explanation for the apparent inconsistency. However, higher priorities precluded him from researching the tunnel history prior to the completion of this study.

of this last observation is that the 5-meter tunnel, with its larger test section cross-section and three-atmosphere pressure capability, more accurately simulates the aerodynamics in many model configurations than does the 12-Foot Pressure Wind Tunnel. Boeing's complaint with the shape of the test section had to do with the circular cross-section of the 12-foot tunnel being non-optimum for the types of testing commonly performed in the tunnel, preferring a square or rectangular cross-section.

Boeing personnel contend that, because their recommendations were not included in the renovated NASA tunnel, it was impractical for them to use the facility after it was completed. NASA's predicament was that the type of funding they used for tunnel reconstitution prevented an improvement in performance. Thus, NASA determined that industry's recommendations could not be accommodated. By the time NASA reopened the 12-Foot Pressure Wind Tunnel, Boeing had spent a decade building a flight database on two different airplanes using the 5-meter tunnel in the United Kingdom, and the company was starting on development of a third airplane. Under those circumstances, they made a decision not to depart from that database and start anew in a different test facility.

Boeing did eventually perform a validation test on a new model 777 airplane at NASA's 12-Foot Pressure Wind Tunnel. However, by that time, Boeing already had a large database from the 5-meter tunnel and other test facilities. In addition, Boeing personnel found that productivity in the NASA tunnel was a problem because the run rate was too low (i.e., relative to the 5-meter tunnel).¹⁷

Boeing personnel advised us that the company's fixed-wing component had never contracted for use of the 40×80-foot and 80×120-foot subsonic wind tunnels at the Ames Research Center. The only use they made of that facility was through participation in a NASA-sponsored test on a large-scale model of the 777 for noise research purposes.¹⁸

¹⁷ The run rate is essentially the number of "runs" (which are a series of data points collected either by either placing the model at a constant sideslip angle—typically zero but sometimes non-zero to check for stability and controllability—and pitching the model through many angles of attack, or by placing the model at a constant angle of attack and yawing the model though many sideslip angles) divided by the charged "occupancy hours" (the time that the model is in the tunnel and the tunnel is capable of productive running).

¹⁸ Fixed-wing military aircraft, such as the F-18 High Angle of Attack Vehicle, have been tested in the NFAC [3].

Full-cost recovery can be a factor that influences customer behavior in such a way as to cause business to migrate elsewhere. In a case that did not involve either the NFAC or the 12-Foot Pressure Wind Tunnel, one customer was planning to conduct transonic wind tunnel tests of the Unmanned Combat Aerial Vehicle (UCAV) at the 11-Foot Unitary Plan Tunnel at the Ames Research Center. However, each NASA center was implementing full-cost recovery at a different rate, and each center has different cost allocation policies. Since Ames was implementing full-cost recovery more rapidly than the Langley Research Center, the customer took advantage of the situation and performed the wind tunnel testing for the UCAV at Langley rather than Ames.

F. Results

We explored the hypothesis that there was a strong correlation or a cause-and-effect relationship between NASA's implementation of a full-cost-recovery policy for its wind tunnels and decreasing use of those facilities by customers. Because several factors contributed to declining use of the test facilities, one cannot fully define the relationship between NASA's implementation of full-cost recovery and declining use of the large/full-scale subsonic wind tunnels at the Ames Research Center on the basis of available usage data.

A number of factors have been responsible for the decline in use of the 40×80-foot tunnel, the 80×120-foot tunnel, and the 12-Foot Pressure Wind Tunnel. The tunnels were all closed for renovation work for extended periods of time during the 1990s, and that caused some customers to use alternate facilities to satisfy their test requirements. After the renovated wind tunnels were re-opened it was impractical for customers to use the wind tunnels at the Ames Research Center to continue work that was ongoing at alternative test facilities, largely because extensive baselines had already been established at the alternate facilities. At least one major potential customer was convinced that the configuration of the renovated 12-Foot Pressure Wind Tunnel was unsatisfactory, and that better test results would be obtained in a wind tunnel in the United Kingdom.

In addition, the Joint Strike Fighter (JSF), which is under development, is being tested in several wind tunnels abroad. That weapon system is being developed for use by armed forces of the United States, the United Kingdom, and potentially several other countries as part of a multinational cooperative development program. Therefore, it was understandable that the developer, Lockheed Martin, would select wind tunnel facilities in several countries (the

United States, the United Kingdom, the Netherlands, and Germany) for testing during the engineering and manufacturing development phase of the JSF [38].

Finally, the declining use of the wind tunnels at NASA's Ames Research Center is taking place at a time when aircraft development in general is taking place at a lower rate in the United States than was previously the case. Funding for rotorcraft research by the DoD and NASA has declined by more than 50 percent from 2001 through 2003, and most of that reduction is attributable to NASA's diminished funding for rotorcraft research and development. The effect that those reductions would have on rotorcraft testing was known years in advance [39, p. 6].

[P]rojected reductions in rotorcraft funding, coupled with the increase in program costs associated with research facilities and other support costs, have resulted in significant slippages and the potential elimination of important rotor wind tunnel tests.

While we were provided anecdotal evidence of situations in which customers chose not to perform their wind tunnel testing in facilities at NASA's Ames Research Center, at least one such issue was resolved by virtue of the customer taking the testing to NASA's Langley Center, where implementation of full-cost recovery was lagging behind Ames. This case provides evidence that pricing can affect wind tunnel usage. Similarly, the Navy had planned to conduct some wind tunnel testing on the JSF in the NFAC. However, after the Navy was informed of the new rates in effect for testing under full-cost recovery, the plans for testing in the NFAC were discontinued.

Based on the foregoing facts and the number of independent variables involved, we conclude that NASA's implementation of a full-cost-recovery policy was only one of several factors responsible for the recent decline in wind tunnel use at NASA's Ames Research Center. As the figures in Table 1 illustrate, there is no regular pattern of diminishing use of the wind tunnels in the NFAC that would correspond with the phased implementation of the full-cost-recovery policy.

While it is not possible to establish a direct cause-and-effect relationship between NASA's gradual implementation of a full-cost-recovery policy and declining use of the subsonic wind tunnel facilities at the Ames Research Center, it is possible to conclude that the full-cost-recovery policy was a factor and that it is likely, now that it is fully implemented, to be a deterrent to the use of NASA wind tunnels in the future.

In commenting on the long-term effects that policies like full-cost recovery can have on utilization of test facilities, the Committee on the Future of the U.S.

Aerospace Infrastructure and Aerospace Engineering Disciplines to Meet the Needs of the Air Force and the Department of Defense raised a significant *a priori* argument [20, pp. 35–36]:

[T]he long-term effect on a facility that is not used extensively is to increase user costs. If an organization cannot afford the increased costs, it will simply stop using the facility. As a result, costs will go up for the remaining users, some of whom will then stop using the facility, and so on. If the facility is scarcely used, a decision may be made to close it altogether, even though the facility may be critical for testing future advanced systems.

Similarly, the Rotorcraft Subcommittee of NASA's Aero-Space Technology Advisory Committee wrote [39, p. 8]:¹⁹

Increased cost to users is very likely to lead to lower utilization of the facilities as budget-conscious program managers find lower cost, albeit less satisfactory, means to accomplish research tasks. This is expected to lead to a spiraling effect of lower utilization and consequently higher cost that would quickly result in a 'death spiral' of unaffordable charges.

If the foregoing rationale is correct, NASA's full-cost-recovery policy could ensure that there will be insufficient utilization of the NFAC and the 12-Foot Pressure Wind Tunnel in fiscal year 2004 to allow either of those facilities to be reactivated by NASA.

¹⁹ The Rotorcraft Subcommittee's report contained a preliminary estimate of the difference between NASA's internal rates for testing in the NFAC and future rates under full-cost recovery [39, pp. 9–10]. "The move within NASA toward full-cost accounting will have a significant impact on the affordability of these facilities for future rotorcraft testing. The internal rate for testing in the NFAC is currently \$1,550 per hour, plus the cost of power. Under full-cost accounting, this rate, which the Army pays when conducting research under the Joint Agreement, will grow to as much as \$7,200 per hour, plus the cost of power."

VI. Forecast of DoD Requirements for Subsonic Wind Tunnel Testing

This chapter assesses the current forecast of requirements for subsonic wind tunnel testing by DoD components and evaluates the process by which recent forecasts were developed. We did not attempt to provide a list of future aircraft development programs (beyond a 5-year horizon) that would benefit from the use of subsonic wind tunnel test facilities. For purposes of this study, it is assumed that the U. S. military and commercial segments will continue to both build and modify fixed- and rotary-wing aircraft for the near future.

A. Recent Forecasts

In the course of our research for this study, we encountered only two relatively recent forecasts of DoD requirements for use of NASA aeronautical test facilities. The first of those forecasts was completed in April 1999. It was the result of a team effort involving the three military departments, and it was accomplished at the request of the Office of the Director, Test, Systems Engineering and Evaluation in the Office of the Under Secretary of Defense (Acquisition, Technology and Logistics). The Air Force provided the forecast summary, and it included the number of hours of testing, by NASA facility, by program, and by fiscal year, from fiscal year 1999 through fiscal year 2005 [40]. The second, and most recent, forecast was prepared by RAND pursuant to the congressionally mandated study of NASA's aeronautical test and evaluation facilities that was funded in the fiscal year 2002 appropriations act for the Department of Veterans Affairs, Department of Housing and Urban Development, and sundry independent agencies to include NASA. It reflected the number of hours of testing, by NASA facility, by program, and by fiscal year, from fiscal year 2003 through fiscal year 2010. We did not ascertain whether or not the projected requirements were actually included in the customers' long-range programs and budgets.

We did not find any joint forecast of DoD and NASA test requirements such as might have been done under the auspices of the Aeronautics and Astronautics Coordinating Board (AACB) or, more specifically, in the spirit of cooperation and coordination of activities "relevant to the use and management of such

(aeronautical test) facilities" prescribed in the National Aeronautical Test Alliance (NATA) Interagency Agreement (Appendix D). Such forecasts have been done in the past, but have not become institutionalized to the extent that they are periodically refreshed. Had such a process been in place, perhaps the problems involving the lack of visibility of test requirements, last-minute test commitments, and the adverse effects to programs resulting from unilateral decisions to close important facilities would have been avoided. In this context, it is clear that the AACB and NATA have failed to achieve at least part of their objectives.

B. Need for Periodic Forecasts of DoD Use of NASA Aeronautical Test Facilities

Now that NASA is fully implementing its full-cost-recovery policy, it is even more imperative for the managers of NASA's aeronautical test facilities and the financial managers at NASA centers and headquarters to have the most reliable information possible on future requirements for the use of those facilities. To properly budget for their workload and workforce, and to develop pricing factors, NASA activities have a more critical need for access to information about what its customers have budgeted for use of the facilities. Procedures that are employed within the Department of Defense for budget formulation could be adapted for exchanges between the DoD components and NASA. In the Department of Defense, customers that are funded in various ways (i.e., with revolving funds and/or direct appropriations) provide one another with forecasted spending as part of the budget formulation process. That way, all activities can plan for the size of their respective workforces, their capital investments, and their contractual obligations.

Under current procedures, NASA facility and financial managers do not have adequate visibility of funded test needs to allow them to confidently retain the personnel and contract support necessary to keep all test facilities open and fully operational.

Part of the difficulty here is that the necessary coordination between the two agencies, as discussed in Section A, is not occurring. Exacerbating the problem is the fact that the DoD has relinquished control of development test program decisions to contractors, and has lost its leverage in gaining reliable forecasts for the use of government facilities, much less the ability to actually require the use of those facilities. This condition is possibly an unanticipated consequence of acquisition reform. During the course of this study, we encountered Government personnel (who prefer to remain anonymous) who believe that the acquisition

policy takes less than full advantage of the test and evaluation process and emphasizes short-term savings that are costing both programs and the Government test and evaluation establishment in the long run, as strategically important facilities go underused, underfunded, and in some cases (such as the one currently being encountered in NASA), potentially eliminated.

C. Arrangements for Use of NASA Test Facilities

NASA and DoD test facility personnel encounter difficulty in obtaining binding commitments from military and commercial program managers to use their aeronautical test facilities. While weapon system program managers are willing to provide NASA with a “pledge” to use the wind tunnels, they are not willing to sign binding commitments to use the wind tunnels. Consequently, in the perception of NASA personnel, DoD program managers can, and often do, wait until it is nearly time to test before actually making the decision about whether to use a NASA tunnel. DoD test facility managers have the same experience.

This practice precludes test facility managers from operating the wind tunnels in the most business-like manner possible.

The Army has been the principal user of the NFAC for its rotorcraft research, which is complemented by NASA research. When NASA curtailed its rotorcraft research commitment and increased the price of testing in the NFAC, the Army was forced to withdraw. The Army wants to continue their work, but the funding difficulties must be resolved first. In the meantime, the facility may be closed and rendered unrecoverable. Likewise, the Navy had planned an important JSF test program in the NFAC. Plans for testing the program in the NFAC were abandoned when the Navy learned of the increase in cost that NASA was planning to impose on NFAC customers. The Navy, unlike the Army, says it can accomplish its test objectives elsewhere, albeit under less-than-ideal conditions. The Army contends that, without the NFAC, advanced rotorcraft research will be severely curtailed in this country.

D. Observations on the Forecasting Process

The problem presented and the solutions posed in this chapter have widespread implications that go beyond the subsonic wind tunnels recently inactivated at NASA’s Ames Research Center. All ground-testing facilities suffer from a lack of accurate workload forecasts. For example, the table in Appendix E was derived from a recent NASA audit report [28]. It shows that, from fiscal year 1997 through fiscal year 2002, projected occupancy hours for all the wind tunnels

at NASA's Ames Research Center were higher than actual occupancy hours in almost every case, and the difference between actual and projected hours was frequently substantial.

In defense of those who ought to be responsible for providing workload projections, the following factors should be taken into consideration:

- The potential user of the wind tunnel is on the same budget cycle as the test facility operator. In other words, the customer is not assured of receiving funds to pay for testing before the tunnel operator must budget for specific support of the test program.
- A DoD program office responsible for an aircraft system usually has planned for certain wind tunnel testing, with the full intent to conduct that testing. It is not unusual for the contractor developing or modifying the system to encounter an unexpected problem that requires immediate additional funding. The money budgeted for the planned testing may be the only discretionary funding available to the program office at the time this event occurs. The program office must then elect to either (1) allocate resources to the solution of a known problem that could have an immediate effect on system performance or even on continuation or (2) retain those resources for a wind tunnel test that might identify and/or diagnose a problem later on. Since any consequences of not testing will become evident only further downstream, the program office often decides to accept the additional risk associated with the avoidance of testing.

E. Capacity and Capability Issues

Apart from annual testing, programming, and budgeting issues that suffer from inadequate workload forecasting, there are more overarching reasons to conduct workload forecasts, particularly for the long term. The issues are workload capacity and capability (having the right number of the right kinds of facilities to accomplish the nation's testing).

The Aeronautics Sub-Group established under the auspices of AACB for the 1995–1996 study [24, p. 89] determined, through a comprehensive assessment of DoD and NASA aeronautical facilities, that the facilities then active represented approximately the right set for the nation's needs, and were "very nearly the minimum required, but that future requirements and examinations might cause a different conclusion." The sub-group's findings were presented in the context of supporting "a viable and competitive industry" in the United States.

Perhaps a conscientious examination of requirements and capabilities, conducted by the NATA under the auspices of the AACB, would have resulted

in a different outcome for the NFAC and the 12-Foot Pressure Wind Tunnel, and it possibly could have helped to bring attention to the problems that have led to the facilities' closure. However, as we stated in the discussion of the interagency agreements in Chapter IV, NASA apparently chose not to use the AACB or NATA to coordinate its activities and plans with the DoD, and the opportunity was lost.

F. Conclusions

The current processes for forecasting requirements for the use of NASA's wind tunnels by DoD components, for programming and budgeting the resources to allow the DoD components to pay NASA for wind tunnel testing support, and for long-range capacity and capability management, are in need of considerable improvement. The coordination called for under the AACB and NATA has clearly not worked. Whether NASA continues to recover fully burdened costs from its DoD customers or modifies its financial policies and practices to recover less than that amount, the customer and service provider need a more effective mechanism to share advance information about workload forecasts.

When both the provider of support and the customer are Federal activities, each one of them requires adequate lead-time to program and budget for the resources required to ensure that necessary work is accomplished. Since a considerable amount of the workforce necessary to operate the tunnels is provided by contract, appropriations must be available to award contracts and make payments for services that are provided by contract. When this is not accomplished through the normal programming and budgeting process, adequate resources can be provided only through extraordinary measures such as reprogramming (which is frequently detrimental to other programs) or supplemental appropriations.

Wind tunnel scheduling is not a predictable process. [10, p. 5] Personnel familiar with wind tunnel testing, from the perspectives of both the customer and the wind tunnel operators, acknowledged that the maximum amount of notice that can be expected with regard to a proposal to conduct a wind tunnel test is about one year.²⁰

²⁰ This conclusion was based on an undated Arnold Engineering Development Center talking paper entitled "Application of DBOF at AEDC" and conversations with Lew Braxton, Chief Financial Officer of NASA's Ames Research Center, on July 22, 2003; David Banducci, Deputy Wind Tunnel Manager at NASA's Ames Research Center, on July 25, 2003; and

We recommend that recurring efforts be conducted to identify future DoD testing requirements that involve the use of Government-operated wind tunnels, similar to the effort completed by the Air Force in 1999 [40]. Resources required to pay for that testing should be identified and included in the DoD components' programs and budgets; and the applicable amounts, together with the associated time frames, should be promulgated to NASA (or other Government providers of wind tunnel services) as soon as practicable. NASA (and other Government providers of wind tunnel services) should be able to rely on those forecasts in order to provide the operating and maintenance resources to deliver quality wind tunnel testing services in accordance with a schedule derived from the forecast. To program and budget for emergent wind tunnel testing requirements, the DoD components may be able to derive some guidelines from reviewing the history of those requirements and program and budget for such contingencies accordingly.

Michael George, Chief of the Wind Tunnel Operations Division at NASA's Ames Research Center on October 31, 2003.

VII. Why Have U.S. Aircraft Companies Developing Weapon Systems for the DoD, and DoD Components Themselves, Chosen to Use Foreign Wind Tunnels?

This chapter addresses the reasons that the DoD components and the supporting U.S. aerospace industry have decided to conduct a number of wind tunnel tests in facilities outside the United States. Appendix C lists selected foreign wind tunnels and gives their locations and fundamental characteristics. Observations on the merits of continued dependence on foreign wind tunnels are contained in the section on Alternative F in Chapter IX.

A. Joint Strike Fighter

The Joint Strike Fighter (JSF) is an international project, and as such, it inherently involves cooperation with participating allied nations. Nine countries are involved in the systems development and demonstration phase of the program [41]. Although U.S.-based Lockheed Martin has been selected to develop the weapon system, the company has encouraged and accepted wind tunnel testing arrangements in foreign facilities. This was evident even during the competition for the JSF program. While competing with Boeing to obtain the contract to develop the aircraft, Lockheed Martin invited Britain's Defence Evaluation and Research Agency (DERA) to bid against American and European rivals to provide wind tunnel facilities as part of the requirements for the Engineering, Manufacturing, and Development (EMD) phase of the JSF program [42]. Working in partnership with Northrop Grumman and BAE Systems to win the competition for the EMD phase, the Lockheed Martin team announced its preference for wind tunnel test facilities. They included facilities operated by Aircraft Research Association (United Kingdom), one of the German-Dutch wind tunnels (a DNW facility) in the Netherlands, and one operated by BAE Systems in the United Kingdom [38]. When Lockheed Martin announced that it had won the competition to build the JSF, the notes accompanying the release indicated that BAE Systems, Aircraft Research Association (ARA), and QinetiQ, all of which are British companies, were on their team for wind tunnel testing [43].

Personnel we interviewed at the Naval Air Systems Command (NAVAIR) stressed the element of international cooperation in the JSF development effort.

They believed that some foreign partners provided wind tunnel testing in lieu of a direct financial contribution. After seeing the results of wind tunnel tests conducted abroad, NAVAIR and contractor personnel gained confidence in the foreign facilities. Lockheed Martin had the responsibility to manage the test program and develop the database. Thus, that company could, and did, decide where that test data would come from.

Notwithstanding these arrangements, on one occasion, the JSF program was compelled to use a foreign test facility that was less capable than the NFAC, largely because of NASA's implementation of full-cost recovery. That situation is discussed in detail in Chapters III and VIII.

B. T-45 Goshawk

NAVAIR personnel advised us that, around 1990, low-speed testing was conducted in the 5-meter tunnel in Farnborough, England, for the T-45. The T-45 is a derivative of the British Aerospace Hawk. A large-scale (30%) model aircraft already existed and had been tested in the 5-meter tunnel. The modified model could be tested in the same facility at three atmospheres to get to a full-scale Reynolds number. In addition, the person in charge of the testing at McDonnell Douglas (the U.S. company responsible for the design of the T-45) had considerable experience with the 5-meter tunnel and was comfortable doing the testing there.

C. P-3C Service Life Assessment Program

The P-3C Life Assessment Program is a joint effort in which the United States is involved with several foreign countries. The NAVAIR Program Executive Office statement of work for the second and third phases of the P-3C service life assessment program provided that the contractor would provide engineering and technical support for wind tunnel testing to be provided in facilities in Canada and England (six weeks in Canada and three weeks in England) [44]. In 2000, the P-3C Life Assessment Program was seeking loads data, and NAVAIR wanted to go to a higher Mach extension with a 6% full-powered model. NAVAIR wanted to test at the low end of the transonic flight regime. Knowing that the United Kingdom's Aircraft Research Association (ARA) had experience testing propellers and had high-speed capability, NAVAIR announced in the *Commerce Business Daily* that it was pursuing a sole-source contract with ARA, contending that "there is only one responsible source and no other...service will satisfy the government agency requirement" [45].

The work was scheduled to take place at the ARA tunnel. However, when ARA postponed the NAVAIR testing to accommodate one of its other customers, NAVAIR used an existing contractual arrangement with the Canadian National Research Center (NRC) to perform the wind tunnel testing in Canada. The P-3C Service Life Assessment Program had been a work-share arrangement with Canada, the Canadians had built the model, and they had the requisite pressure in their tunnel. However, NAVAIR was not able to test above 250 KCAS (calibrated airspeed in knots) in the Canadian tunnel, whereas they had hoped to test at 400–500 KCAS at the ARA facility in England.

NASA's Ames Research Center submitted a quote for the P-3C wind tunnel testing. However, the Ames Research Center did not have the equipment to test powered motors on propellers at the time, and it would have been necessary for NAVAIR to pay for the necessary developmental work at the tunnel. That additional cost was more than NAVAIR could afford to pay for the test.

D. E-2C Hawkeye

NAVAIR advised us that there is a requirement for propeller testing for the E-2C. NAVAIR is currently soliciting bids from foreign wind tunnels because, although Lockheed Martin has done some propeller testing, no U.S. test facility has the requisite experience to conduct this 9-month test. NAVAIR is planning to conduct a powered test of propellers at high Reynolds numbers. NAVAIR personnel want to test two motors at 300 HP each, using a pressure tunnel in which they have the capability to build a large-scale (1/8 scale) model. Essentially, they are pursuing a high-fidelity database on a high performance propeller aircraft. They need a tunnel that uses either a hydraulic or pneumatic motor in order to get beyond the capabilities of an electric motor.

NAVAIR proposes to rotate the hub balances during testing, and rotating balances have recently been developed in Europe that have been successfully used in wind tunnel testing of propeller-driven models at one of the ONERA wind tunnels in France [46]. NAVAIR personnel prefer to use a wind tunnel in which the operators have current experience with that type of testing.

NAVAIR conducted a survey and considered wind tunnels in the United States, Canada, England, France, and Switzerland. At the time this report was being prepared, NAVAIR was narrowing the choice to either the RUAG Aerospace large subsonic wind tunnel in Emmen, Switzerland, or an ONERA wind tunnel at Le Fauga-Mauzac, near Toulouse, France.

E. Other Foreign Wind Tunnel Testing

While it is not our intent to provide an exhaustive survey of foreign wind tunnel tests conducted by U.S. aerospace companies, some other examples might serve to show the frequency with which such testing takes place. In the early 1990s, NASA engaged in a cooperative arrangement with the United Kingdom's Defence Research Agency (DRA) to conduct research on rotary flow aerodynamics. NASA contracted with Bihrlle Applied Research, Inc., for the wind tunnel testing involved in that effort. The testing was performed in the DRA's low-speed atmospheric tunnel in Bedford, England, and the high-speed pressurized tunnel in Farnborough, England [47]. One Bihrlle corporate officer explained that those tests involved specialized equipment that permitted higher Reynolds number testing than could be obtained in the United States.

A Congressional Research Service report published in 1995 indicated that, at that time, U.S. manufacturers were using European wind tunnels for 25 percent of the testing time involved in the development of a new airplane. The rationale was that the technology and the capability to simulate actual flight conditions in a cost-effective manner was considered better in Europe, and the costs were more favorable in some cases [48, pp. 2 and 21–22].

Boeing has also been conducting wind tunnel tests on its Delta IV rocket in countries around the world. Articles that discussed some of that testing described tests that were conducted in France and Canada [49 and 50]. One of the tests performed in Canada was conducted in a tunnel that specializes in the simulation of ground winds.

F. European Quality, Security, and Value

High-lift testing on the F-18 was conducted in England when the 12-Foot Pressure Wind Tunnel at the Ames Research Center was down for reconstruction. Personnel at NAVAIR suggested that testing of the F-18 revealed that European facilities test well. We were advised that the managers of the English tunnels are researchers, and they have input into what is done in their test facilities. It was alleged that in the United States, test managers are likely to accede to user preferences as to cost, schedule, or other business considerations, often sacrificing quality. Aircraft Research Association (ARA) in the United Kingdom has been known to insist that certain components of a test be included, leaving the customer no choice but to accept them. The result is that ARA's data quality remains high.

Boeing personnel advised us that they have pursued testing in foreign facilities because they were not satisfied with the reconstruction of the 12-Foot Pressure Wind Tunnel at the Ames Research Center (see the discussion in Chapter V, Section E). Boeing officials were not only disappointed with the tunnel configuration, they also found that NASA operators were less motivated than the operators of the QinetiQ facility to make the tunnel available to the next user in a timely manner. When Boeing performed a validation test on a new model 777 at NASA's 12-Foot Pressure Wind Tunnel, they found that the run rate was too low. According to one Boeing official, even if NASA were to give Boeing more favorable rates, it would still be less economical for Boeing to use the 12-Foot Pressure Wind Tunnel than the 5-meter tunnel because of the length of time required to get the testing done in the NASA facility. From the standpoint of cost per data point, Boeing finds it advantageous to use the QinetiQ facility. In fact, Boeing has already established a 15-year history of using QinetiQ's 5-meter tunnel at Farnborough, England, in lieu of the 12-Foot Pressure Wind Tunnel at the Ames Research Center. Boeing used the 5-meter tunnel for the 737 next-generation family of aircraft, the 767-400ER, and the 777. It should be noted that NASA has planned use of its test facilities primarily for aerodynamic research. Consequently, the NASA facilities are not staffed or operated to achieve the productivity level of either the DoD's Arnold Engineering Development Center or some of the European facilities.

NAVAIR personnel also commented that their input was not used in the reconstruction of the 12-Foot Pressure Wind Tunnel at Ames. They expressed concerns about the size and shape of the test section as well as the support system. With respect to the F-18E, the modeling of the flaps under the wing can be done better in England because of the larger scale. However, they noted some problems with data taken at high angles of attack. Above a certain angle of attack, they saw a divergence from flight data as flap angle and Reynolds number increased. Even with the problems noted, NAVAIR personnel believed that the 5-meter tunnel in England would be preferable to the 12-Foot Pressure Wind Tunnel for pressure testing.

In a 1994 report, the Aeronautics and Space Engineering Board cautioned that European competitors have potential access to the data generated when U.S. aircraft manufacturers use European wind tunnels [51, p. 18]. A Congressional Research Service report released the following year contained the following statement, which was based on an interview with a Boeing representative [48, p. 22]:

Although test information that a U.S. company is paying for at a foreign wind tunnel is, by agreement, supposed to be known only to the company

using the tunnel, it is often difficult to ascertain where the test data does go when being transferred from the recording instruments in the tunnel to nearby computers for storage. In addition, visual access by foreign wind tunnel personnel is almost as significant as actual electronic data access.

Nevertheless, when we asked Boeing personnel about security, they replied that they have high confidence that the company's test data in England is being kept secure and not being turned over to its European competitor. When Boeing uses the QinetiQ wind tunnel, a product security team goes out in advance and conducts an inspection. Boeing puts an extra information system firewall in place when they test at QinetiQ. Boeing personnel also advised us that QinetiQ's data system is isolated from the rest of its network. However, Boeing personnel would not be equally confident that their test data would be protected in some other foreign wind tunnels.

Boeing personnel provided a comparison with respect to the availability of test data. They contend that, at least in the past, NASA wanted to check their test data before providing it to the customer, and that process might take up to two weeks. By contrast, other test facilities gave them access to their data sooner. Boeing has the capability to go into the test facility and simultaneously gather its own data with its own equipment so that the company can have immediate access to the data.

In 1994, the Aeronautics and Space Engineering Board of the National Research Council stated that, due to national security concerns, foreign facilities were particularly inappropriate for the development of military aircraft [51, p. 19]. Several NAVAIR personnel that we spoke with in conjunction with this study maintained that program managers responsible for classified programs would definitely want to avoid the risk of using foreign wind tunnels, where their data and models were subject to being compromised. However, one DoD official interviewed for this report indicated that a U.S. special access program had been tested in a foreign wind tunnel and that the testing DoD component was confident that the test data were secure. One customer informed us that, at one of the DNW tunnels, each customer has a secure preparation hall for the construction of models.

Some personnel that we interviewed for this study (Billy Barnhart, Vice President of Bihrlle Applied Research, Inc., and Andrew W. Kerr, Director, U.S. Army Aeroflightdynamics Directorate) informed us that the European wind tunnel operators had greater flexibility than their NASA counterparts to offer

wind tunnel services at reduced rates.²¹ If a U.S. customer is enticed to take testing work to those tunnels, and if the customer is satisfied with the testing services provided, the customer is likely to continue to use that facility. As Boeing pointed out with respect to its experience with the 5-meter tunnel, it can be expensive for the customer to revert to use of alternative tunnels in the United States, where it may be necessary to build an entirely new testing database.

With respect to NASA wind tunnels, the foregoing perspectives of customers do not appear to have changed much in the past 15 or 20 years. The following excerpts from a 1987 assessment of NASA's major wind tunnels are both revealing and somewhat prescient [52, pp. IV-13 through IV-15]:

In virtually all of the facilities, staffing limitation is a major factor in restricting productivity in all phases of a test program.... Model preparation and buildup are frequently done in the test section rather than in separate preparation areas, causing a loss in test time of up to one-half of that available. Typical industry comments...are...staffing limitations contribute to intolerably slow data reduction and analysis in some facilities and to inordinately time-consuming model changes and facility preparations. Staffing levels at some development facilities operated by the USAF at AEDC are more than twice those at comparable NASA tunnels....[S]urvey results reveal a widespread industry opinion that the NASA facilities are antiquated, are not well maintained, and consequently are not reliable. Utilization is reduced significantly by shutdowns for scheduled and unscheduled maintenance, repair and construction....The research tunnels' staffing and support functions...are geared to the research program resources....[M]any potential outside users are discouraged from utilizing these facilities because backlogs for other tests are excessive or because NASA cannot commit firmly to schedules consistent with development program requirements. Although the NASA facilities are attractive to outside users, lack of productivity and manpower prevents their full utilization by industry....[T]he Ames facilities...data systems and displays are less current than those of other Centers. Since the Ames tunnels are generally the largest in NASA and most suitable for supporting fast-paced development programs requiring large amounts of data, their deficiencies have serious consequences.

²¹ One indication of how rates at European facilities compare with NASA's fully burdened rates can be found in an article that appeared in an Ames Research Center newsletter in 1999. In that article, the author contends that with various European governments subsidizing wind tunnel operations, the Ames Research Center would have difficulty competing with their pricing when it charges full cost [10, p. 3].

In 1997, the DoD Aeronautical Test Facilities Assessment concluded that [22, p. 52]:

The Europeans are leading the United States in test technology research through their Group for Aeronautical Research and Technology in Europe....This organization has enabled the European facilities to exceed the capabilities of...comparable U.S. facilities in many areas.

In 1999, an article that appeared in an Ames Research Center newsletter contained the following observation [10, p. 3]:

Dwindling government funding in major aeronautics programs, combined with our major facilities being shut down for extended periods for renovation, has sent customers seeking the “best value” in wind tunnel test support. They have found it in a variety of facilities in Europe.

G. Conclusion

U.S. aerospace companies and DoD components have been using foreign wind tunnels for years.²² Most foreign wind tunnel testing that was brought to our attention for purposes of this study was, or is being, conducted in either Western Europe or Canada. Some foreign wind tunnel testing was initiated because of the need to find alternative wind tunnels when wind tunnels at NASA’s Ames Research Center were closed for several years due to renovation. Other foreign testing seems to be the direct result of international cooperative efforts such as the development of the Joint Strike Fighter and the cooperative agreement for research into rotary flow aerodynamics between NASA and the United Kingdom’s Defence Research Agency. In some cases, a foreign facility was used simply because it specialized in the type of testing that was required. We were also advised that some foreign wind tunnel testing was provided to U.S. entities at prices that were more favorable than NASA was able to offer.²³

In most cases, U.S. customers of European test facilities were favorably impressed by the quality and productivity of those tunnels as well as the

²² As the following excerpt from the DoD Director, Operational Test and Evaluation Fiscal Year 1998 Annual Report indicates, DoD has been aware of this situation for several years. “[T]he DoD relies on NASA at Langley, VA, for wind tunnel support. However, reductions in NASA budgets have contributed to lack of investments to revitalize these facilities to the level of readiness needed to support DoD requirements. Some DoD test and evaluation requirements can only be satisfied by the use of facilities and ranges outside of the United States” [53, pp. II-8-II-9].

²³ See Section F of this chapter.

professionalism of the test staff and the management. Security of classified and proprietary data, as well as the test models, remains a concern when foreign tunnels are used. Several U.S. customers were satisfied with the security of their data and their models at selected foreign facilities, but they were definitely wary of some foreign facilities.

Each U.S. contractor selects the most appropriate and cost-effective test program for its aircraft development testing. For a variety of reasons previously noted, this often leads to the use of foreign wind tunnels. This trend is likely to continue unless sufficient resources are invested in U.S. facilities to make them technically and economically attractive, and the U.S. Government exerts some influence on its contractors to use U.S. test capabilities.

VIII. Effect on the DoD and the Supporting U.S. Aerospace Industry

This chapter identifies the effect of the closure of the subsonic wind tunnels on the Department of Defense and the supporting U.S. aerospace industry. It concludes with the authors' assessment of the long-range effects of those closures and NASA's full-cost-recovery policy.

A. Rotorcraft Development

The closure of the NFAC is particularly significant for the rotorcraft industry. Bell Helicopter personnel advised us that, in comparison to the NFAC, the ONERA S1MA and the DNW tunnel are inferior in size, access, and test rigs. In addition, those tunnels are not supported by NASA expertise. Bell Helicopter personnel advised us that lack of sufficient size would be a particular problem for testing advanced concepts such as the quad tilt-rotor. Smaller wind tunnels in the United States cannot accommodate models of the quad tilt-rotor at sufficient scale.²⁴

Bell Helicopter personnel indicated that they did not know what they would do for wind tunnel testing if the NFAC were no longer available. They did not appear to be interested in testing on the European continent since they were concerned about information security when testing in foreign countries. They would, however, have some confidence in security of their information in Canadian test facilities.

There were three rotorcraft tests planned at the NFAC at the time it was inactivated. Two of those tests involved the use of a UH-60 Blackhawk rotor system, which was installed in the tunnel when it was closed. First, a NASA-

²⁴ With rotorcraft, the size of the test section in a wind tunnel is critical. "One of the key concerns underlying any wind tunnel investigation is the impact of the tunnel test section on the test model (and rotor) aerodynamics and performance, and the determination of installation configurations and/or tunnel correction methodologies that minimize that influence. This is a particularly crucial issue for hover performance measurements in an enclosed wind tunnel environment. Wall effects, including flow recirculation, can be considerable if the rotor diameter is too large, or the disk loading too high, for the test section" [54, p. 4].

initiated study of Individual Blade Control was underway, with actuators replacing pitch links to provide higher harmonic pitch inputs to the blades. The objective was to study the ability to control vibration and noise, in addition to improving performance, and to provide the data required to develop and correlate analysis techniques for use in the design and development of active-control rotors. Just prior to closure of the NFAC, the rotor components were overstressed during testing, resulting in the need to replace some of those components before testing could be resumed. Due to competing priorities for spare parts for Army helicopters in the Iraqi war at the time, parts were unavailable for use on a research article. However, the Army could resume that testing in FY 2004 if the wind tunnel were open and funding were available.

The second test was a UH-60 rotor scaling study. That test is the culmination of a 20-year effort by NASA and the Army to (1) accurately predict rotorcraft performance, aero-elastic stability, acoustics, and loads and (2) improve the effectiveness of wind tunnel testing in the vehicle development process. Large discrepancies exist in the ability to predict the detailed loading on helicopter rotors in flight and in wind tunnels. The rotorcraft technical community cannot match rotor trim, loads, and acoustic data between flight test and wind tunnel test results. There are unresolved differences between wind tunnel data obtained from small versus large-scale tests. NASA had planned a series of experimental programs to pursue a solution to that problem.

Blades for the full-scale and model-scale testing of the UH-60 rotor were made in the late 1980s. The Army and Sikorsky invested approximately \$2 million in the design, fabrication, and testing of a 9.4-foot diameter, highly instrumented, scale-model UH-60 rotor for testing in the DNW wind tunnel in 1989. Hence, scale-model testing of the rotor was accomplished well in advance of flight testing of the full-scale rotor.

NASA invested approximately \$2 million in building an identically instrumented set of full-scale, flight-worthy rotor blades for the UH-60. However, the development of a data system to capture all the high-bandwidth data from the full-scale blades in flight was not completed until 1994. In 1994, the Army and NASA completed an extensive flight test of that rotor. There are major discrepancies between the scale-model wind tunnel and full-scale flight measurements. Wind tunnel testing of the full-scale rotor was delayed while the NFAC was down for upgrading and pending the development of a wind tunnel test stand large enough to accommodate the UH-60 rotor.

During the 1990s, the Army and NASA invested a total of \$12 million in the development of a large rotor test stand to enable the testing of rotors with

diameters of up to 60 feet in the NFAC. This Large Rotor Test Apparatus was used for the first time to run the Individual Blade Control experiment, with minimally instrumented UH-60 wide-chord rotor blades that were 54-feet in diameter. NASA's plan, prior to the cancellation of its Rotorcraft Research and Technology Base Program, was to test the highly instrumented NASA flight rotor in the NFAC. That test would obtain data that was critical to attempting to resolve the scaling problem and determine if methods for more accurate use of small-scale data could be developed in the future to support advanced rotor concept and systems development efforts. This test could proceed immediately if access to the NFAC were available.

The third rotorcraft test that was planned for the NFAC at the time of closure was a test of the Smart Material Active Rotor Technology (SMART) Rotor, which is being developed by a consortium headed by Boeing under the sponsorship of the Defense Advanced Research Projects Agency (DARPA), supported by NASA. This was to be a test of a high-order rotor control technology. In the test, the blade flaps would be independently controlled to give a torsional movement to the rotor in order to vary rotor twist and reduce vibration.

The fabrication of the SMART rotor has been completed and, in October 2003, checkout was initiated on a whirl tower at Boeing. The Army would still like to do wind tunnel testing of the SMART rotor for 6–8 weeks in FY 2004.²⁵

The bottom line is that, for all three of the foregoing tests, the unavailability of the NFAC has caused rotor research and development to be delayed at least one year. If the NFAC is not brought rapidly back on line, the lack of large-scale testing capability will require entirely restructured research approaches to substitute small-scale models or flight programs to obtain less accurate data, at comparable or significantly increased cost. Consequently, rotor technology development will be delayed several years.

In addition, the Director of the Army's Aeroflightdynamics Directorate believes that, if money were available, the V-22 Program Manager would be interested in doing wind tunnel testing of the Tilt Rotor Aeroacoustic Model (TRAM) in the NFAC. The TRAM is a ¼-scale, full-span (two rotor) model of the V-22. The model, which was recently completed through a combined (NASA and

²⁵ In the long term, the Army is considering funding the Variable Geometry Advanced Rotorcraft Demonstrator (VGARD) Program. The SMART rotor is essentially a precursor of the VGARD. The rotor for the VGARD program has embedded computer-controlled actuators for on-blade control.

Army) investment of \$15 million, is ready for testing. Personnel at Bell Helicopter stated that the TRAM only fits in the NFAC, and it is useful in understanding a number of low-speed aerodynamic phenomena that apply solely to rotorcraft. The TRAM's rotor has been tested in a DNW wind tunnel as a single, isolated rotor, but it is necessary to test a full-span configuration in a wind tunnel to obtain the actual flow field experienced by the aircraft. Bell Helicopter asserts that the NFAC is the only wind tunnel that is capable of exploiting the TRAM as a tilt-rotor vehicle research test bed.

Other advanced rotorcraft concepts, such as heavy lift helicopters, the quad tilt-rotor, and the Unmanned Combat Armed Rotorcraft (UCAR), are best tested at large or full scale. The UCAR, which is envisioned for about 2015, uses an innovative anti-torque propulsion concept. With respect to that system, Bell Helicopter personnel informed us that full-scale testing is essential because it is not possible to test the engine-empennage configuration in small-scale wind tunnels.

Acoustics testing is also important for rotorcraft research and development.²⁶ The Director of the Army's Aeroflightdynamics Directorate advised us that a wind tunnel used for rotorcraft acoustics testing should have the following characteristics:

- The background noise level should be at least 10 decibels lower than the rotor noise itself.
- The cutoff frequency of the facility should be low enough to measure low frequency sounds (around 80 Hz for meaningful rotor low-frequency noise measurements).
- Measurement instrumentation should be located far from the source of the noise (5 to 10 times the rotor diameter away from the rotor).
- The test section should be closed so that it is not necessary to take the remote measurements through the shear layer of an open test section.

In the 1990s, the DNW-LLF tunnel in the Netherlands was the world-class wind tunnel for acoustics testing. When the 40 × 80-foot test section of the NFAC was outfitted with acoustical upgrades, the DNW tunnel was used as a benchmark. Following the upgrades, it has the abovementioned characteristics. If the NFAC is permanently closed, DoD components and the U.S. aerospace industry will be limited in their ability to test at a full range of critical

²⁶ In a telephone interview on June 19, 2003, Blair Gloss, NASA Facility Group Director for Wind Tunnels, Aerothermodynamic and Aeropropulsion Facilities, opined that the best subsonic acoustics tunnels in the United States are now closed.

frequencies, and they will be required to use facilities outside the United States to do additional acoustic testing of rotors related to detectability and identification.²⁷ Such tests are done best when they are performed as close to full scale as possible. Thus, the NFAC is the optimal wind tunnel for the testing of large rotors.

The effect of the closure of the NFAC is not entirely limited to those programs and organizations that actually planned to conduct tests in that facility. John Shaw, Chief Scientist at Boeing Rotorcraft, advised us that, while Boeing Rotorcraft in Philadelphia operates its own 20×20-foot wind tunnel, the organization still uses data from other programs that are tested in the NFAC. Therefore, he can vouch for the value of the NFAC and would be reluctant to see tests that would otherwise be conducted in the NFAC taken abroad because the tunnel was closed.²⁸

In addressing the importance of the NFAC, the Rotorcraft Subcommittee of NASA's Aero-Space Technology Advisory Committee said [39, p. 9]:

The decision to rely more on low-fidelity simulation and sub-scale tests rather than full-scale tests and high-fidelity simulation could, in some cases, result in unnecessary risks for rotorcraft development programs.

NASA's decisions to curtail funding for rotorcraft research and to close the NFAC could have far-reaching consequences for both military and commercial rotorcraft in the United States. In July 2002, in its third interim report, the Commission on the Future of the United States Aerospace Industry stated [15, p. B-37]:

The long-term cooperative efforts between NASA and the DoD in rotorcraft research are in serious turmoil. As NASA faces internal budget pressures, it has sought to eliminate all of its rotorcraft R&D activity unilaterally. In the face of a growing European rotorcraft industry, the future competitive U.S. capabilities in both military and commercial rotorcraft technology development is in serious jeopardy.

Insofar as rotorcraft research and development are concerned, the NASA decisions addressed in this study are particularly critical from both the short-term and the long-term perspectives.

²⁷ Identification in this context refers to the ability to identify a specific type or model of aircraft without visual confirmation by means of an aural or acoustic signature.

²⁸ Telephone conversation between John Shaw, Chief Scientist, Boeing Rotorcraft, and Terrence Trepal, October 30, 2003.

B. Testing to Support Research

Wind tunnel testing is often considered in the context of design support for military or civil aircraft. The research community's needs for wind tunnel support are generally given less priority. Yet, the products of that research demonstrate the advances in technology that permit the evolution of new aircraft systems. Researchers have requirements for the most reliable flight simulation in test facilities in order to prove and extend their hypotheses. The NASA wind tunnels that are being closed have proven most useful for that purpose.

The 12-Foot Pressure Wind Tunnel for many decades provided U.S. military and civil aeronautical researchers unique information that led to improved aircraft performance. Tunnel characteristics of high Reynolds number, large size, and low turbulence permitted study and optimization of various wing configurations and their landing flap systems. Most of our modern aircraft have benefited from this research, with improved range and fuel efficiency as well as more effective wing configurations for take-off and landing. While the aircraft industry has found alternative test facilities overseas (in England and France) for support of aircraft design, the research community has been less fortunate.

Research is often an iterative process and best accomplished in readily available, easily accessible wind tunnels that permit several test article modifications and changes in the testing program. Further, research programs do not usually have the financial resources that would permit the use of foreign test facilities. It is possible that the variance in aircraft wing treatments on U.S. and European aircraft is already influenced by the unavailability of the 12-Foot Pressure Wind Tunnel for a decade of research activity.

The argument for use of the NFAC for research purposes is even more compelling. The discussion of rotorcraft development in this chapter adequately illustrates this premise. Not only will rotorcraft research programs be curtailed by the use of alternative test facilities, but also the researchers will be forced to use premature flight testing to investigate full-scale aerodynamic effects. Both cost and risk are increased, and the iterative research process is compromised.

C. Termination of Full-Scale Testing

With the closure of the NFAC, there will no longer be a capability to conduct full-scale testing of aircraft in any wind tunnel in the United States. In fact, it is highly unlikely that the DoD or the U.S. aerospace industry will be able to conduct full-scale testing of aircraft at any wind tunnel in the world. Now that the NFAC has been inactivated, the only active, operational wind tunnel of

comparable size in the world is Russia's Central Aero-Hydrodynamics Institute's T-101 tunnel, which has an elliptical test section that is approximately 79×46 feet. However, caution must be exercised with respect to ascertaining the capabilities and condition of the Russian tunnel, as well as the security of any models that are placed in the tunnel or any data that is extracted from it.

Generally, the larger the test section, the larger the model that can be tested in the wind tunnel, and larger models yield more accurate test data. [48, p. 7, fn 26] Large tunnels provide other benefits, including ease of model fabrication, incorporation of remote control surfaces that enhance tunnel productivity, and better access to models being tested [55].

D. Emergency Testing

If the NFAC and the 12-Foot Pressure Wind Tunnel are permanently closed, neither of those tunnels would be available to a DoD component or a U.S. aerospace company to conduct wind tunnel testing in response to a bona fide emergency, such as catastrophic failure of a particular military aircraft. This would be particularly detrimental with respect to the NFAC because of its unique size. The problem would be exacerbated if the failure occurred in a military helicopter or tilt-rotor aircraft since rotor data quality is greatly diminished in smaller tunnels.

E. Joint Strike Fighter

At the time that the Ames Research Center announced the inactivation of the subsonic wind tunnels, Lockheed Martin's Joint Strike Fighter Program Office was planning to conduct wind tunnel testing of the Short Take-Off Vertical Landing (STOVL) inlet configuration on the aircraft. The JSF has a bifurcated inlet system. Two induction inlets on the sides of the fuselage are the primary air induction system during regular flight. However, from zero velocity, with sideslip in all directions, up to 300 knots, lift is provided by a system with an inlet on top of the fuselage located behind the canopy that works in conjunction with the side inlets. To adequately test this configuration, Lockheed Martin needed a large model in a large tunnel. They selected the NFAC.

The imposition of full-cost recovery drove the price of the JSF test to an unacceptable level, and the Lockheed Martin program office declined to test in the NFAC. At that time, NASA had already curtailed its funding for rotorcraft support, and no funded rotorcraft testing was firmly scheduled for the NFAC in

fiscal year 2003.²⁹ Consequently, the JSF was the only remaining viable test on the NFAC schedule, a factor that greatly contributed to the high price quoted by NASA. To conduct that test, the JSF would need to bear the cost of operating and maintaining the tunnel, including overhead, without assistance from other customers. In addition, the JSF Program Office at Lockheed Martin was not willing to accept the risk of possibly needing to go back into the facility to refine some aspect of the design only to find it closed. It should be noted that the Joint Strike Fighter Program Office considered the scheduled test to be critical to the development of the aircraft and had already invested substantial resources in preparation for it – many of which were of no benefit in the test at an alternative facility (DNW).³⁰ It is also significant to note that with the move to the DNW tunnel, the JSF Program Office accepted a reduction in test capability and the risk associated with it.

F. Long-Range Implications

Although the scope of this effort is limited to the effect of the proposed closure of the subsonic wind tunnels at the Ames Research Center, it is strongly related to a broader issue. While we could not conclude that NASA's implementation of its full-cost-recovery policy was the sole cause of the closure of the subsonic wind tunnels at Ames, there are strong indications that it is a major factor in ensuring that those tunnels remain closed during fiscal year 2004. The consequence is that the tunnels can be expected to close permanently.

However, full-cost recovery is now being implemented throughout NASA, and the Ames Research Center was actually ahead of at least one other NASA center in the implementation process. It is foreseeable that the implementation of that policy at other centers could hasten or cause the closure of other NASA wind tunnels in other flight regimes. To the degree that the DoD and the U.S.

²⁹ Rotor and rotorcraft tests were also scheduled to take place in the NFAC but could not be conducted at the time for reasons described in Section A, Rotorcraft Development, previously in this chapter.

³⁰ To get the proper simulation, the wind tunnel must be able to pull air through the simulated ducts. Lockheed Martin could have done that in the NFAC because it had the size and the capabilities to get the job done. Since there was no obvious choice of an alternative wind tunnel after the inactivation of the NFAC, Lockheed Martin looked at the AEDC complex, the DNW LLF tunnel in the Netherlands, and the French ONERA S1MA tunnel. Although the DNW tunnel did not have the capability to pull air through the inlets on the model, Lockheed Martin now plans to pay to put Roots blowers, which are auxiliary suction systems, in the DNW tunnel to conduct the necessary testing.

aerospace industry rely on NASA for wind tunnel testing, further closures would only exacerbate the effects addressed in this study.

The inactivation of the subsonic wind tunnels at the Ames Research Center has resulted in the loss of both government and contractor personnel whose expertise was extremely valuable to research, development, and test and evaluation. The Ames Research Center wind tunnel staff has been reduced from 286 people (180 contract personnel, 106 civil servants) in fiscal year 1999 to only 60 (30 contract personnel, 30 civil servants) in fiscal year 2003 [56]. Among the departing personnel are individuals who have specialized knowledge concerning the operation and maintenance of the wind tunnels as well as the conduct of testing in those facilities. The perspective of the former AEDC Commander is illuminating [20, p. 35]:

Modifications and additions to basic test facilities, as well as changes to operating modes, are not always recorded in any formal way; they may exist only in the memories of operating personnel. In this sense, test facilities are similar to manufacturing facilities in which critical so-called black-book knowledge is vital to efficient operations. Therefore, decisions to deactivate a facility should take into consideration the effects of losing the personnel who know how to reactivate and operate the facility.

The closure of the large-scale wind tunnels compels the DoD components and the aerospace industry to adopt alternatives such as using smaller wind tunnels (with scaling problems and a resulting loss of data fidelity), premature flight testing of aircraft, reliance on CFD data that was not validated in wind tunnels, and dependence on foreign wind tunnels. In many cases, use of foreign wind tunnels seems to be the alternative of choice. There are risks associated with dependence on foreign test facilities, including the possibility of losing a position of international leadership in aeronautics.³¹ That in turn, could result in the United States' turning to other nations for the acquisition of even more

³¹ In its report to the NASA Aero-Space Technology Advisory Committee, documenting the results of its August 1999 meeting at the Ames Research Center, the Rotorcraft Subcommittee said, "NASA management must make hard choices to either support aeronautics and rotorcraft with adequate budgets, or give up U.S. leadership" [34, p. 3]. In an e-mail message, dated November 10, 2003, Conrad A. Ball, Boeing's Director, Laboratories and Test Technologies, stated: "Boeing is in a life or death competition against a rival that is subsidized at all levels. We are therefore compelled to find the most cost effective means to acquire the data that meets our technical and schedule requirements. If the lack of investment in the U.S. aero research capabilities continues, we will be forced to use European facilities. This places the future of U.S. aerospace industry at risk: our schedules will be at the mercy of our competitors and we risk leakage of our critical proprietary technologies."

commercial aircraft and eventually for acquisition of some military aircraft. That would be potentially detrimental to the interests of the United States in the event that the U.S. military were dependent upon foreign sources for parts and aftermarket support at a time when the United States was taking military action that did not have international support [57].

IX. Analysis of Alternatives

This chapter identifies several alternatives for DoD subsonic wind tunnel testing in the wake of NASA's announcement to close wind tunnel facilities at the Ames Research Center at the end of fiscal year 2004 if sufficient workload does not materialize to allow them to operate on a self-sustaining basis. There are eight alternatives displayed in order of preference from the authors' perspective, with the most highly recommended alternative first. The advantages and disadvantages of each alternative are presented. Those alternatives are ways the DoD can address the immediate effects of the closure of the subsonic wind tunnels. Generally, the DoD has the ability to either initiate or implement one of those alternatives in the near term.

Following the alternatives, two long-range options are included for consideration. Neither one of those options is a substitute for adopting one of the alternatives. To pursue either of them would require the DoD to obtain support from organizations other than NASA. Either option can be expected to take several years to implement, and a successful outcome cannot be presumed.

The alternatives and options are as follows:

- Alternatives (in order of preference):
 1. Assume ownership of or lease the NFAC (and possibly the 12-Foot Pressure Wind Tunnel), assume operational responsibility, and upgrade the facilities to meet current and future needs.
 2. Prevail upon NASA to continue to maintain and, as necessary, operate the large/full-scale subsonic wind tunnels (and possibly the 12-Foot Pressure Wind Tunnel) at the Ames Research Center.
 3. Assume ownership of or lease the NFAC (and possibly the 12-Foot Pressure Wind Tunnel) and assume operational responsibility without upgrading or modifying the facilities.
 4. Construct state-of-the-art subsonic wind tunnels using Military Construction Appropriations to restore national testing capability.
 5. Use alternative wind tunnels in the United States.
 6. Conduct large/full-scale subsonic testing in foreign wind tunnels.
 7. Increase reliance on computational modeling and simulation in lieu of wind tunnel testing.

8. Maintain the status quo.
- Options (in no particular order):
 1. Establish an independent agency with ownership and operational responsibility for major U.S. aerospace test facilities.
 2. Privatize the inactivated subsonic wind tunnels or transfer operational responsibility to a non-Federal organization.

A. Alternatives

The eight prioritized alternatives that follow offer benefits that can be obtained in the short term in most cases. The fourth alternative offers a mid-term solution, but should be accompanied by a short-term measure to provide interim relief until the alternative is fully implemented.

1. Alternative 1—DoD Ownership and Operation with Upgrades

In this scenario, the DoD would either take possession of the NFAC and possibly the 12-Foot Pressure Wind Tunnel outright or acquire operational control of the facilities through a long-term lease or other use agreement that would effectively transfer ownership and operational responsibility (and authority) to the DoD for the remainder of the facilities' useful life. The transfer of facilities to the DoD would be contingent on Congress appropriating funds for the upgrade and modernization of the facilities.

a. Advantages

This alternative would protect facility investments that have already been made, requiring relatively modest funds to upgrade and modernize the facilities when compared to the design and construction of new ones. Upgraded, modernized facilities would serve the nation's low-speed aeronautics Research, Development, Test and Evaluation (RDT&E) needs for years to come.

Transfer of ownership of the facilities to the DoD would place the facilities under the control of the governmental department that needs them. Both rotorcraft research and development and fixed-wing testing could be done in facilities that would be reliably available and secure with respect to the protection of sensitive information, thereby alleviating the concerns about testing in foreign facilities.

Under DoD management, the facilities could be operated in a high-production mode, providing products on a more cost-effective and timely basis. Under NASA operation, the facilities are operated more as laboratory facilities;

and this is reflected in higher cost per data point and longer time to deliver test results than, for example, a typical wind tunnel test at AEDC.³² If the DoD were to upgrade the wind tunnels, one potential improvement would be the modernization of data acquisition systems, which should result in an increase in productivity.

DoD management would also place the pricing of tests in the tunnels under the partial cost-recovery model of the Major Range and Test Facilities Base. That would provide some relief to the customer, although, as noted in Section D of Chapter V, customers had previously migrated from DoD to NASA facilities, ostensibly to seek lower cost. In this case, there would be no “free” alternative available.

b. Disadvantages

While the cost would be small compared to building new facilities, upgrades and modernization of the facilities would probably require at least a one-time, near-term expenditure to achieve desired performance levels. The actual cost of modernization and upgrades would depend on the number and types of investments selected.

Keeping the existing facilities operating in place would mean continued interaction with encroaching neighbors, environmental constraints, high labor rates, and potential power shortages that affect Ames Research Center facilities.

c. Discussion

This approach is highly desirable because it avoids the high cost of building new facilities and requires only the investment of upgrade and modernization capital. The approach provides a path to return to critical rotorcraft and fixed-wing research and development with minimal investment.

d. Conclusion

This is the recommended alternative because it provides the technical capability required to continue rotorcraft research and to meet fixed-wing large-scale low-speed requirements. The nation’s aeronautics capability and previous investment can be preserved with a relatively small capital outlay by first transferring the affected wind tunnels to the DoD to be operated in place and

³² NASA wind tunnels are located at research centers. The test facilities and the staff are oriented toward research rather than production.

then upgrading and modernizing those facilities. If the DoD could afford to absorb only one of the wind tunnel complexes, the NFAC would be the one most critical to DoD requirements.

2. Alternative 2—Prevail Upon NASA for Continued Operation

Under this alternative, the DoD would prevail upon NASA to continue to maintain the NFAC, and possibly the 12-Foot Pressure Wind Tunnel, and operate the wind tunnels as necessary to satisfy customer requirements. Even if sufficient workload did not materialize for continuous self-sustaining operations, NASA would maintain the tunnels at a level of readiness that would permit them to be activated for testing within an agreed-upon period of time (e.g., 30 or 90 days).

a. Advantages

The principal advantage to this alternative is that the tunnels would remain available to customers in the DoD and the supporting aerospace industry on a continuing basis. This alternative can be implemented without a change of ownership or management, and personnel who presently have the training and experience to operate those specific tunnels would likely be retained for that purpose. The loss of what many subject matter experts believe to be unique national assets would be avoided, and the U.S. rotorcraft industry would have the means to continue research and development of more complex helicopters and tilt-rotor aircraft with both military and civil applications. Emergent requirements for large/full-scale subsonic wind tunnel testing of the type experienced by developers of fixed-wing aircraft could be satisfied through test facilities available in the United States in lieu of uncertain access to foreign wind tunnel test facilities. Security of U.S. test data and models would be adequately protected.

b. Disadvantages

Implementation of this alternative would require an estimated \$10 million to \$15 million per tunnel per year for NASA to operate and maintain the tunnels. NASA estimates that it would cost \$4.3 million per year to maintain the NFAC in a standby status with the capability to operate the tunnels within 3 months. Similarly, NASA estimates that it would cost about \$1 million per year to maintain the 12-Foot Pressure Wind Tunnel in the same standby status. The primary reason for the difference is that the latter facility is newer and requires less maintenance. The last two figures (i.e., \$4.3 million and \$1 million) are the estimated costs to maintain the wind tunnel facilities in standby status. They do

not include either the additional staff members that would be required to prepare for, and conduct, a test or the costs to restore the facilities and associated equipment to the point where it is possible to resume testing. Reactivation of the subsonic wind tunnels would involve replacement of the data systems that have been removed from those facilities. It is highly unlikely that the tunnels could be maintained, even in a standby status, if the requisite funding is to be derived solely from customers of the wind tunnels under NASA's current full-cost-recovery policies.

The trained and experienced workforce required to operate the tunnels must be retained through some extraordinary measures. The relevant operating and maintenance procedures would have to be documented fully and carefully to allow for the training of additional personnel and for future reference.

c. Discussion

Our rationale for support of this alternative is primarily that it involves minimal disruption of existing facilities and arrangements, while avoiding many of the higher costs and risks associated with other alternatives addressed in this report.

NASA has reassigned most of the Government workforce and released most of the contract workforce associated with operating and maintaining the NFAC. Given adequate resources, NASA could cross-train some of the remaining personnel at the Ames Research Center so that they can be used when the NFAC and the 12-Foot Pressure Wind Tunnel are in operation. However, those personnel are required for the operation of the Unitary Plan Wind Tunnel, the transonic and supersonic wind tunnel complex at the Ames Research Center. A cadre of experienced retirees willing to return to work for specific projects could augment the workforce at the Ames Research Center.³³ Such personnel would require periodic training for purposes of both refreshment of memory with respect to information they have already learned and updates when new instrumentation is incorporated into the facility or new testing techniques are developed or adopted.

Funding would be the most formidable obstacle to implementing this alternative. NASA's current full-cost-recovery policy would make customers responsible for paying the fully burdened costs of operating and maintaining the

³³ While this is a possible short-term measure, it would be inadvisable to rely on retirees for too long a period of time. Eventually, they will find it desirable or necessary to leave the work force.

tunnels, including times when the facilities are not in use. Therefore, prospective customers would find the associated prices to be prohibitive.

A different approach would be for NASA to charge customers (at least Federal customers and perhaps domestic corporations as well) for the direct costs of using the wind tunnels and seek a direct appropriation for the core costs of maintaining the NFAC (and the 12-Foot Pressure Wind Tunnel) in an operable condition. The authority to charge customers less than fully burdened rates is contained in NASA's Financial Management Manual.

The combination of customer funding for the direct costs of their respective tests and an infusion of direct appropriations to defray the expenses of maintaining those unique facilities as national assets would allow NASA to continue to support aeronautical development without jeopardizing its space mission or other programs in order to do so.

There is an approach-avoidance conflict associated with the foregoing financial solution. It clearly leaves the decision to the Congress to provide the resources necessary to ensure that these wind tunnels continue to exist and serve as national assets. The risk is that, if members of Congress are not persuaded by the merits of that position or do not see sufficient value in maintaining those test and evaluation facilities, this financial solution would fail.

d. Conclusion

This is a desirable alternative. It assumes that the responsibility for maintaining unique national assets like the NFAC (and the 12-Foot Pressure Wind Tunnel) properly belongs to the Federal Government, and that the private sector, while being expected to pay its full share of operating costs for testing conducted on its behalf, would not share directly in the core costs of maintaining those facilities.

The alternative assumes that the DoD and NASA can reach an agreement on the requirement to keep the NFAC (and possibly the 12-Foot Pressure Wind Tunnel) open and operational, notwithstanding the inability of the wind tunnels to generate sufficient revenue from normal operations to be self-sustaining. It may require communications at a sufficiently high level in both organizations as well as negotiations with the Office of Management and Budget.

If there are not enough resources available to maintain both the NFAC and the 12-Foot Pressure Wind Tunnel, priority should be given to maintaining the NFAC because of its unique features and greater value to the DoD components and the supporting U.S. aerospace industry.

3. Alternative 3—DoD Ownership and Operation without Upgrades

In this alternative, the DoD would take possession of the NFAC (and possibly the 12-foot Pressure Wind Tunnel) outright, or would acquire operational control of the facilities through a long-term lease or other use agreement that would effectively transfer ownership as well as operational responsibility (and authority) to the DoD for the remainder of the facilities' useful life. However, the DoD would neither modify nor upgrade those wind tunnels, except as required to bring them up to operational status.

a. Advantages

This alternative would protect facility investments that have already been made, eliminating the need to secure major new investment funds.

Transfer of ownership of the facilities to the DoD would place the facilities under the control of the governmental department that needs them. Both rotorcraft research and development and fixed-wing testing could be done in facilities that would be reliably available and secure with respect to the protection of sensitive information.

Some efficiencies would also be gained by the incorporation of DoD high-production operational procedures not employed by NASA.³⁴

The pricing advantage that could be expected under DoD management, discussed under Alternative 1 in this chapter, is also applicable here.

b. Disadvantages

The facilities in question each have moderate to major deficiencies that need to be corrected. Failure to do so would have little or no effect on most of the testing that is to be done in them, but in some cases could lower the fidelity of data, limit the useful life of the facilities, or cause customers to pursue their testing requirements in alternative facilities. Simply transferring ownership or control to the DoD would not solve the problems related to tunnel condition and capability.

Keeping the existing facilities operating in place would mean continued interaction with encroaching development, environmental constraints, high labor rates, and potential power shortages.

³⁴ A greater gain in operational efficiency would be possible through an upgrade of the facilities under Alternative 1.

c. Discussion

This approach is supportable because it avoids the high cost of building new facilities and requires only the investment of initial recovery costs and the maintenance costs required to preserve the facilities. The approach provides a path to return to critical rotorcraft and fixed-wing research and development with minimal investment.

d. Conclusion

This alternative provides much of the technical capability required to continue rotorcraft research and to meet most identified fixed-wing, large-scale, low-speed requirements. However, it is not a fully acceptable long-range solution to the nation's full-scale, low-speed test needs or its requirements for low-speed, high Reynolds number subscale test facilities. Like Alternative 1, the desirability of this alternative would be greatly enhanced if it included upgrades of the facilities in question.

If there are not enough resources available to operate and maintain both the NFAC and the 12-Foot Pressure Wind Tunnel, priority should be given to maintaining the NFAC.

4. Alternative 4—Military Construction of New Tunnels

Under this alternative, the DoD would seek Military Construction (MILCON) appropriations to design and construct at least two major wind tunnel test facilities to replace those being closed at the NASA Ames Research Center. The facilities to be replaced are the NFAC (includes two test sections, one 40 × 80 feet and the other 80 × 120 feet), and the 12-Foot Pressure Wind Tunnel. Rather than duplicate the existing facilities, which represent 20- to 50-year-old technologies, the alternative proposes the design and construction of state-of-the-art replacements.

a. Advantages

The advantages of reestablishing the capabilities of the NFAC and the 12-Foot Pressure Wind Tunnel using MILCON are fourfold:

First, the MILCON approach would allow new design and construction, enabling the acquisition of technologically up-to-date facilities capable of being operated efficiently and cost-effectively to produce superior aeronautical systems for many years to come. The new facilities could be located away from foreseeable encroachment and environmentally undesirable areas.

Second, an investment through the MILCON appropriation would establish ownership of the new facilities in the Government department where the principal need for them exists, namely the DoD. Bell Helicopter personnel advised us that rotorcraft research and development, being a strong driver for the full-scale tunnel, is needed for future uninhabited military air vehicles over hostile territory and in homeland defense scenarios where toxic chemical or biological releases are suspected to be a factor. Heavy-lift rotorcraft are needed for rapid deployment and supply of outposts in both military and homeland defense scenarios. In addition, tilt-rotor and high-speed stowed-rotor aircraft will require research and development testing. There are needs in the area of high-lift configurations of fixed-wing aircraft, and they are largely driven by military applications.

Third, DoD-owned facilities would eliminate the risks of limited access and security issues that accompany dependence on foreign facilities.

Finally, the existing facilities are currently located in a high-cost, congested, environmentally constrained, and sometimes power-limited location. Reestablishing the capabilities at a properly chosen site elsewhere would eliminate many current and potential future operational challenges.

b. Disadvantages

Under this alternative, facilities that are “good enough,” in the case of the NFAC, will be prematurely discarded. With a relatively low investment compared to building replacement facilities elsewhere, the NFAC could be modernized and made viable for many years to come. The 12-Foot Pressure Wind Tunnel, which was recently rebuilt from the ground up—albeit to outdated standards because of constraints on the use of the upgrade funds—could be modified to meet current standards. A modification could probably be done at significantly lower cost than that required to reestablish the capability in its entirety.

The cost of reestablishing the capabilities elsewhere would be substantial. Current estimates, actually educated guesses, range from \$350 million for a new full-scale wind tunnel to \$1 billion or more for each new wind tunnel facility, thereby setting the total cost of both an NFAC and a 12-Foot Pressure Wind Tunnel replacement in the neighborhood of \$2 billion or more. The Director of Military Construction in the Office of the Secretary of Defense (Comptroller) told us that obtaining such a large MILCON appropriation would be very difficult. Many factors, including the number of years over which the appropriation may

be spread and the politics surrounding the project, will be important in obtaining the necessary funding.

Historically, the time to gain approval for the design and construction of a major new test facility is substantial, and may be expected to range from 10 to 15 years from concept to initial operating capability. That means either some interim measures would be needed to ensure the retention of existing facilities until the new facilities are ready or the DoD would have to accept the risks of dependence on foreign facilities.

c. Discussion

New wind tunnels funded through MILCON are the most desirable alternative from purely technical and national security standpoints. They provide the most up-to-date capability for development of superior technologies and systems, and they are reliably available when needed to support critical defense and homeland security needs. However, as indicated above, implementation of this option would need to be accompanied by an interim solution.

From a cost perspective, the MILCON alternative presents a major challenge. The climate in recent years has not been conducive to making major investments in infrastructure; it has been the opposite, more attuned to divestiture of infrastructure. In fact, this trend has created the current crisis with respect to the low-speed tunnels in question.

d. Conclusion

New state-of-the-art facilities owned by the DoD represent a highly desirable alternative from a technical standpoint, but the construction of those facilities might not be practical. The cost of design and construction of completely new facilities in a new location is probably prohibitive in today's environment.

5. Alternative 5—Use Alternative Tunnels in the United States

This alternative assumes that the NASA Ames low-speed tunnels are not available or viable for supporting DoD testing. Either the tunnels are permanently closed, mothballed in a manner that prevents their reconstitution in a timely manner to support a given test program, or the agency sponsoring the test program deems the charges for use of the facility unaffordable. Effectively, the alternative requires the program manager to use either subsonic wind tunnels with smaller test sections or transonic or supersonic wind tunnels operating at subsonic speeds. In this context, it should be noted that, in 1994, the

Aeronautics and Space Engineering Board of the National Research Council recommended that consideration be given to the construction of a dual-use wind tunnel with both low-speed and transonic capabilities [51, p. 20]. The Central Aero-Hydrodynamics Institute (TsAGI) in Russia uses its T-128 wind tunnel for testing at both transonic and subsonic speeds [48, p. 25]. NASA and Lockheed Martin used the Joint Strike Fighter Concept Demonstration Aircraft Model to validate that the 10×10 -Foot Supersonic Wind Tunnel at NASA's Glenn Research Center is a viable subsonic test facility from the standpoint of data quality [58].

a. Advantages

The advantage of this alternative rests on the assumption that other test facilities in the United States are satisfactory to the system developer. There are several, smaller low-speed wind tunnels in industry and NASA that could support the type of testing in question. They are presently used for research and development, and they are less expensive to use because of the reduced cost of test articles and lower tunnel operating costs. For example, the power to drive the air in a wind tunnel is proportional to the test section area. Thus, if one compares Boeing's 20×20 -foot low-speed tunnel with the 80×120 -foot tunnel at the Ames Research Center, the power factor is 24 times greater in the 80×120 -foot tunnel. Other than costs, there are advantages of convenience and security when compared with the alternative of using foreign test facilities.

b. Disadvantages

Smaller low-speed test facilities in the United States existed when the NASA 80×120 -foot tunnel was constructed. However, the Government and industry considered the improvement in test capability to be adequate justification for an expensive construction project. The NFAC and 12-Foot Pressure Wind Tunnel need to be considered separately for purposes of this analysis. The larger facility offers world-class testing opportunities with full-scale hardware. The 12-Foot Pressure Wind Tunnel is not world-class, but it is the best offered in the United States. There are no other U.S. test facilities designed to provide this low-speed, high Reynolds number capability on similar sized test articles.

The large transonic and supersonic wind tunnels in the United States could be configured to partially accommodate some of the testing workload of both NASA test facilities that are being addressed. These facilities are not so large as the NFAC (16-foot square versus $40 \times 80 \times 120$ feet) and cannot be pressurized as high as the 6-atmosphere, 12-Foot Pressure Wind Tunnel. Such facilities have

drive motors that are much more powerful than those of the low-speed facilities, and they use considerably more energy. They can be made to operate at low-speed conditions, but at significantly higher power consumption than a facility designed to operate at subsonic speeds. This energy inefficiency, which translates into high operating cost, makes this approach moderately acceptable for emergency or short-term situations, but highly undesirable as a permanent alternative.

Adoption of this alternative would have an adverse effect on the rotorcraft industry because rotorcraft airflows are more complicated. Wall effects are significant, and scale takes on greater importance with active rotors.

c. Discussion

There is some question as to whether or not program managers and aircraft developers would adopt this alternative. They may instead use large-scale wind tunnels in foreign countries or conduct flight tests without adequate ground testing.

This alternative rests on the hypothesis that the test customer would turn to other U.S. facilities. The most likely U.S. facilities to be used are:

- Boeing's 20×20-foot V/STOL tunnel; Mach No. 0–0.3 (Philadelphia, PA)
- Lockheed Martin's 16×23-foot low-speed tunnel; Mach No. 0–0.24 (Marietta, GA)
- NASA's 14×22-foot VTOL tunnel; Mach No. 0–0.3 (Langley Research Center, VA)

However, the trend to turning toward foreign test facilities, particularly the German-Dutch Wind Tunnels (DNW) and the British 5-meter tunnel, has already manifested itself. It appears that the 5-meter tunnel in the U.K. is the facility of choice, even after NASA's 12-Foot Pressure Wind Tunnel was returned to operational condition. That is not the case with respect to the NFAC, since there is no other tunnel in the United States or elsewhere that matches the capability of the NFAC. U.S. developers have used the DNW tunnels in the past during periods in which the NFAC was unavailable. Their familiarity with the DNW tunnels heightens the likelihood that U.S. developers would accept the DNW alternative rather than run the risk of incurring the additional cost of paying to keep the NFAC open. This reflects the historical behavior of the U.S. military program offices and aerospace industry when confronted with choices that involve either accepting what is available or paying the cost of a better

alternative. That is not to say that U.S. developers prefer inferior facilities; it is simply that they are not funded to carry the burden of maintaining national test infrastructure. History also tells us that the results of such decisions are not immediate; they show up later in the form of less-than-optimum-performing flight systems with attendant expensive corrections and program delays. Therefore, it appears that the use of other U.S. facilities as primary alternatives to the NFAC and the 12-Foot Pressure Wind Tunnel is unlikely as long as acceptable and affordable foreign alternatives remain available.

d. Conclusion

If adopted, this alternative would likely result in lower data quality for wind tunnel tests because the benefits of testing with large-scale models would be eliminated. If the option of using transonic or supersonic tunnels is selected, it will be more costly to conduct wind tunnel tests because of increased power requirements. Finally, selection of this alternative would be particularly harmful to rotorcraft development in the United States, because rotorcraft testing is best accomplished with large or full-scale models in large test sections.

6. Alternative 6—Use Foreign Wind Tunnels

This alternative assumes that the National Full-Scale Aerodynamic Complex (NFAC) will be closed and possibly demolished, and that, at least for the short term, no replacement facility would be constructed in the United States. Under those circumstances, the alternative addresses the possibility of compensating for the loss of the NFAC by conducting large or full-scale subsonic tests in either Canadian or European wind tunnels. Although there are wind tunnel facilities in other parts of the world, we have chosen to focus on Canadian and European facilities because of their geographical proximity to the United States and because they have been the facilities of choice for those DoD components and U.S. aerospace companies that have already elected to conduct large-scale wind tunnel testing outside the United States.

a. Advantages

The principal advantage to this alternative is that it should provide for continuation of large-scale subsonic wind tunnel testing following the closure of the NFAC, without any hiatus for the construction of a replacement facility. It also would avoid the substantial capital investment involved in replacing the NFAC and even the costs of maintaining the NFAC in a standby status. Testing would be conducted in facilities that are more modern, and at least ostensibly,

more productive than the NFAC. At least initially, it appears that the cost of using foreign wind tunnel facilities for large-scale subsonic testing should be no greater than the cost of paying fully burdened rates to NASA for use of the NFAC, and sometimes the cost would actually be lower.

b. Disadvantages

Implementation of this alternative would involve certain inherent risks. The three principal risks brought to our attention are potential breaches of security, possible periods of unavailability, and the likelihood of future cost increases and limitations on access and availability.

Security of the data and the models belonging to DoD components or U.S. aerospace companies that conduct testing in foreign facilities is a serious consideration, although it is likely to vary according to both the type of testing being conducted and the country in which the tests are performed. Periods of unavailability may materialize because of competing requirements of customers with higher priority or as a result of political considerations. Once it becomes evident that the United States has lost its large-scale subsonic test facilities and is dependent upon the foreign wind tunnel(s) to conduct such tests, prices and limitations on access and availability could increase.

In addition to the foregoing general disadvantages, adoption of this alternative would be particularly detrimental to rotorcraft development in the United States. The rotorcraft industry has the most compelling requirement for full/large-scale wind tunnel testing and would be forced to conduct testing in facilities where the dominant users are direct competitors for both technological superiority and market share.

c. Discussion

Several U.S. aerospace companies and DoD activities have reported a certain amount of satisfaction with the use of wind tunnels in Canada and Western Europe. Some would argue that the foreign tunnels selected are better managed and more productive. We have been advised that the German-Dutch Wind Tunnels (the DNW) have newer control systems and newer data systems than the NFAC. In addition, users have reported that rates for utilization were no greater than rates they would be charged by NASA. The managers of foreign wind tunnels have the flexibility to charge lower rates, particularly if there is any benefit to the host nation that can be derived from the U.S. tests.

The conduct of wind tunnel testing at facilities in the United Kingdom may be enhanced by bilateral arrangements that are under consideration for

Cooperative Test and Evaluation Programs [59 and 60]. The concept paper in Appendix G addresses reciprocal use of test facilities, the sharing of test and evaluation information, and a customer-provider relationship in which testing services are provided at preferred rates (i.e., direct costs).³⁵ We understand that similar arrangements are already in effect with Canada and France, and that the United States is developing one with the Netherlands as well.

In some cases, U.S. entities using foreign tunnels reported being pleased with security arrangements in effect at certain facilities. In one case, a classified project was tested in a foreign wind tunnel, with the United States in complete control of the instrumentation and the data. We were also told that DNW has a completely secure area for the preparation of the model to be tested. Obviously, concerns about the security of test data and models vary by location and circumstance. For example, some corporate officials we interviewed for this study expressed far more comfort with testing military aircraft in English tunnels than they would have with testing commercial aircraft in other foreign countries.

Security of data and models is important from two perspectives. From the standpoint of the aerospace industry itself, there is a need to protect proprietary information in terms of test data on the one hand and design specifications or configurations on the other. From the perspective of the DoD, there is also a need to protect information about the development or modification of weapon systems from the standpoint of national security. The latter situation is of significance for purposes of this report.

Availability is an important factor in the selection of a wind tunnel. If the tunnel is unavailable when the customer needs it, an aircraft's development could be considerably delayed. If not, other alternatives that involve greater risk or greater cost might be substituted for ground testing in a wind tunnel. Foreign wind tunnels already have a customer base, and the government of the country in which the test facility is located effectively subsidizes many such tunnels. Hence, if a company like Airbus Industries already is the dominant user of a wind tunnel, and that company is in the midst of a lengthy and complicated test program, U.S. forces or U.S. aerospace companies may be forced to wait until the tunnel becomes available before they can begin testing in that facility. Similarly, political considerations could affect availability of the test facility. For example, the U.S. Government's recent decision to initiate military action in Iraq was not

³⁵ The concept paper in Appendix G was developed by the Office of the Director, Operational Test and Evaluation, with the assistance of the Office of the Director, International Cooperation.

supported by a number of European nations. The governments of such nations could seize the opportunity to make their wind tunnels “strategically unavailable” as a means of communicating their dissatisfaction with the United States or to further their own goals such as dominance in aeronautics by the year 2020. The European vision for aeronautics in 2020 clearly demonstrates that (1) world leadership in that area is a European objective, (2) the United States is considered the primary competitor, and (3) expanded cooperative arrangements, combined with increased funding for aeronautical research, is perceived as the vehicle to achieve global leadership [61].

Finally, we need to consider the possibility of significant cost increases materializing after the large/full-scale subsonic wind tunnels in the United States are irrevocably closed. This situation could be exacerbated by the eventual demolition of those wind tunnels. It is analogous to the bargaining position that a sole-source provider has in a contractual arrangement with the United States. Once there is no longer a viable alternative, and the U.S. Government or the U.S. aerospace industry becomes completely dependent upon the foreign test facilities, the managers of those facilities will have the opportunity to increase their charges for use of those tunnels, leaving the U.S. Government and the U.S. aerospace industry in a relatively weak bargaining position.

d. Conclusion

Reliance on foreign wind tunnels involves risks. For the short term, it is feasible to judiciously conduct subsonic wind tunnel testing in selected highly reliable wind tunnels in foreign countries. DoD components and U.S. aerospace companies have already demonstrated that it can be done. In cooperative arrangements, such as the development of the Joint Strike Fighter, it allows other nations to contribute to the effort, and all nations involved have a mutual interest in the data. For some of them, free or reduced-price wind tunnel testing may be the most effective way to contribute to the developmental effort. However, for the long haul, particularly in situations in which the United States is engineering new military technology, the uncertainty of adequate security and availability make reliance on foreign wind tunnels risky.

Reliance on foreign wind tunnels may be particularly detrimental to the U.S. rotorcraft industry, which is already falling behind its European competitors. Certainly, foreign countries that are gaining market share in the sale of rotorcraft are unlikely to be motivated to allow U.S. companies to use their subsidized facilities to do the developmental work necessary to regain some of that market share. If U.S. companies come into facilities used by major

competitors (e.g., Eurocopter), to test cutting-edge technologies, the security of proprietary data and model configurations is likely to be placed at risk.

Appendix C contains a list of selected large-scale wind tunnels capable of conducting tests in the subsonic flight regime. Occasional use of foreign subsonic wind tunnels may be an acceptable means of compensating for the unavailability of domestic wind tunnels. It may be possible to ameliorate some security risks by careful selection of reliable foreign wind tunnels in allied nations and the effective use of international agreements. But the long-term consequences of total dependence on foreign test facilities are likely to prove unacceptable. Such long-term dependency could leave the U.S. aerospace industry, in particular, the rotorcraft component of that industry, vulnerable to considerable loss of market share. Such dependency also increases the likelihood that the United States will fall behind competitors in aeronautical development. That, in turn, could ultimately lead to U.S. dependence on foreign sources for the acquisition of advanced military and dual-use aircraft, as well as aftermarket support.

7. Alternative 7—Greater Reliance on Computational Fluid Dynamics

This alternative considers the extent to which numerical modeling can replace the need for NASA's low-speed test facilities. Recent improvements in modeling techniques, coupled with advances in computer speed, permit computational fluid dynamics (CFD) to provide more realistic estimates for external flows around aerodynamic shapes. CFD is a component of the process known as Numerical Aerodynamic Simulation [48, p. 25, fn 102].

a. Advantages

CFD provides the opportunity to readily control many design variables without the complication of physical models and unsure simulation parameters in a wind tunnel. Computational modeling and simulation complements wind tunnel testing as it contributes to the design of the aircraft model that is tested in the wind tunnel, reduces the scope and magnitude of wind tunnel testing via interpretation and extrapolation of data, and provides some guidance for the selection of test parameters in wind tunnel simulations. Also, once models have been reconciled with test data, changes to configurations can be evaluated less expensively than with wind tunnel testing.

The usefulness of numerical modeling is not limited to fluid flow behavior; it also addresses heat transfer, mass movement, mechanical movement, deformations of solid structures, and other phenomena relevant to aircraft

design. Thus, CFD is extremely useful for purposes other than aerodynamic modeling.

b. Disadvantages

The vision of full dependence on computational methods for design of aircraft is far from a reality. The complications of three dimensions, unsteady flows, cross flows, and modeling of the surface characteristics of real hardware provide researchers real opportunities for improvement, even for incompressible flow fields. While CFD is a valuable tool, it has primarily reduced the testing that was conducted in small company wind tunnels.³⁶ Test facilities that provide good environmental flight simulation sometimes see an increased workload brought about by the need to validate numerical models. The Army helicopter community notes that the complications of flow unique to helicopter rotor blades and similar lift aircraft place them many years behind fixed-wing aircraft in the development of validated numerical models.

A recent NASA Technical Memorandum, which was produced by NASA and Boeing personnel, contained the following statement about the current level of confidence in CFD [63, p. 1].

The aerospace industry is beginning to utilize CFD and trust its results and/or trends near design conditions where there is little or no separated flow; but there is currently little confidence in CFD's ability to predict flows involving significant amounts of separation.

c. Discussion

In the mid-1990s, the cost per data point when using CFD was estimated to be roughly equal to the cost of 600 wind tunnel data points [64, p. 4]. However, the cost of simulating aerodynamic flow by computer has been steadily decreasing, while the cost of wind tunnel testing has been increasing. Plans call for a database with validated numerical models, as well as the computer speed and capacity to permit design of new rotating and fixed-wing aircraft across the entire speed-altitude flight spectrum. Particularly with the use of microprocessors, the hardware to compute complex flow fields has steadily improved since the mid-1970s. It has been predicted that, while wind tunnel testing may become two to four times more productive, the productivity of CFD

³⁶ A recent article that appeared in *Aviation Week & Space Technology* stated: "Progress in CFD has resulted in fewer wing designs being tested in the wind tunnel, dropping from 77 for the Boeing 767, to 18 for the 777, to perhaps as low as five for the 7E7...." [62, p. 61]

will increase by several orders of magnitude. If hardware improves by two orders of magnitude and software improves by two to three orders of magnitude over a 10-year period, the cost of a computed data point may decrease by four or five orders of magnitude over that time. Hence, the cost per data point may soon be equal for CFD and wind tunnel testing. The cost of making equivalent improvements in wind tunnel facilities, by contrast, will be comparatively expensive and involve lengthy construction lead times. Some experts anticipate that the combination of competition from CFD and advancements in measurement technology will result in a decline in the number of wind tunnel tests required in the development of a new aircraft. [64, pp. 3–6; and 65, pp. 23 and 30] If those predictions actually materialize, fewer wind tunnels could be needed. However, the need to better match flight simulation parameters in those wind tunnels will not diminish.

David Lednicer, of Analytical Methods, Incorporated, summed up the current relationship between CFD and wind tunnel testing well [66, p. 6]:

While it has often been stated that CFD will replace wind tunnel testing, experience has shown that, instead CFD complements wind tunnel testing. While wind tunnel testing is very expensive, but relatively low risk, CFD is much cheaper, but has a higher risk of producing misleading or incorrect results. Taken together, CFD, coupled with wind tunnel testing, reduces the technical risk in developing a new design and allows engineers to refine a design further than previously possible.

In December 1996, a DoD Workshop on Future Aeronautical Needs for Wind Tunnel Testing and CFD concluded [22, p. D-3]:

Broad categories of difficult problems remain for which current CFD methods are inadequate to provide predictive capability. These include a fundamental understanding of turbulence, chemically reacting flows, massively separated flows at flight Reynolds numbers, unsteady flows, transitional flows, aeroacoustics, hypersonic nonequilibrium flows, plasma flows, compressible flows involving complex geometries, multielement wings, two-phase flows, strongly vortical flows, and noncontinuum flows.

At the same workshop, the participants opined that the computer speed and memory required for routine application of Direct Numerical Simulation to practical problems at flight Reynolds numbers could very well remain unavailable for a minimum of 40 years [22, p. D-4]. “The workshop’s participants concluded that extensive use of CFD to replace wind tunnel data was 20 to 40 years away” [22, p. S-2].

A number of subject matter experts interviewed for this study strongly support continued (or improved) emphasis on computational fluid dynamics and numerical modeling and simulation. Conventional wisdom requires using all the numerical tools in the arsenal before committing to a design. In the design of aircraft, this includes producing an aerodynamic model that is subjected to a simulated flight environment in one or more wind tunnels. Aircraft design is usually an iterative process, with CFD used to interpret and sometimes extend wind tunnel results.

These arguments are further supported by a recent article in *Aerospace America*. The author notes [67, p. 20]:

Computational fluid dynamics (CFD) has always been surrounded by an aura of promising possibilities. It is of extreme academic interest, because the mathematical equations stemming from the physics are quite complex. Even with modern-day computers and supercomputers, the equations are not completely solvable. Assumptions are made to reduce the complexity of the boundary conditions or 3D surface.

d. Conclusion

For the near future, computational modeling and simulation will be used in concert with wind tunnel testing of physical models. To commit to an aircraft design that was based purely on numerical simulation would entail unacceptable risk. In Boeing's development of the 777, computer modeling was used extensively. Yet, the complementary wind tunnel program was substantial (20,000 hours) [48, p. 9], even though the 777 configuration was not a drastic departure from other Boeing aircraft. CFD has not reached, and most likely will not reach, a state of maturity such that it can be used to populate a design database exclusive of experimental data.

8. Alternative 8—DoD Take No Action

Obviously, one alternative is for the DoD to remain mute on this subject. That could be the result if the DoD waits for other interested parties to take action, hopes that NASA reverses its intended plan for facility closures, or simply discounts the seriousness of the situation.

a. Advantages

Since the DoD's acquisition policy has placed responsibility for "development" and its attendant testing on the prime contractor, this situation

might be considered industry's dilemma. Certainly, a lack of action would avoid the DoD's need to expend resources directed toward a solution to the problem.

b. Disadvantages

The closure and unavailability of major aerodynamic test capabilities is not just a DoD problem; it is a national problem. Failure to take action could easily permit that problem to grow to the point where the Department of Defense and the supporting U.S. aerospace industry are so adversely affected that the damage will be extremely difficult and costly to correct. Since the development of military aircraft is dependent upon use of both DoD and NASA test facilities, the DoD would be prudent to recognize the implications of NASA's intended actions. The DoD must ensure that its business is not affected and that the United States does not become unduly dependent upon foreign countries for testing that is essential to aeronautical research and development.

c. Discussion

It will be difficult to find parties who will demand that NASA's test facilities remain viable. Such demands will likely be met by a response that requires such parties to incur financial obligations to keep those test facilities open and operational. Within elements of the DoD, recognition of the problem is a two-step process. First, one must be convinced that development testing (or lack of same) is a DoD concern in aircraft development. Then one must accept that it is essential for the Government (DoD and NASA) to own and operate the test resources used for development testing. No contractor will step forward and say that he must have any given test facility to stay in business. The contractor will simply use lesser test capabilities, take greater risk, and likely build more expensive products with reduced performance. Some of the alternative test facilities are located overseas. In past years the justification for building better test facilities in the United States was that the competition had better development tools than this country did. Is this no longer a concern? Can the United States be considered a major aeronautical power when it must depend upon the cooperation of others to design and build aircraft? If the trends that we have observed in the preparation of this study continue, the wind tunnels at NASA's Ames Research Center remain closed, and the DoD takes no action to reverse this situation, it is foreseeable that dependence on international partners will result in the United States turning to foreign sources for military aircraft and the satisfaction of future mobility requirements. [13 and 68]. At a minimum, it is advisable to heed the words of the DoD Director, Operational Test and Evaluation [27]:

There is an inherent risk in becoming totally dependent on facilities outside the United States. We cannot stay competitive in the aerospace world market or in the areas of national security if we are dependent on others for fundamental test capabilities.

d. Conclusion

We strongly recommend that the DoD acknowledge the impending dilemma and begin cooperative efforts to effect a satisfactory solution to the void created by the loss of the subsonic wind tunnels at the Ames Research Center.

B. Options

The following two options are solutions that, if pursued, would not take effect for years. Thus, they are considered long-term solutions.

1. Option 1—Independent Agency for U.S. Aerospace Test Facilities

This long-range option would require legislative action. It would result in the creation of an independent agency of the U.S. Government that owns major aerospace test facilities and operates them for the benefit of both military and civil research and development. Congress would appropriate funds for the operation of those test facilities (or the portion of operating costs not recovered through reimbursement from customers). Fees assessed agencies of the U.S. Government and U.S. aerospace companies would be limited to the direct costs of conducting their respective tests in the Government facilities.

a. Advantages

This option places the responsibility for the budgeting for the requisite capital investment and the core operating costs to keep unique national aeronautical test facilities operating in the hands of a single agency charged with that specific mission. Consequently, the amounts budgeted and appropriated for the construction, maintenance, and operation of those test facilities would not be in competition with other components of that agency's budget or other parts of its mission. It would support the DoD, NASA, other Federal departments and agencies, and the U.S. aerospace industry in accordance with priorities established by law and regulation. Elimination of unnecessary duplication of facility capabilities should be effected more easily if DoD and NASA test facilities were centralized under one agency. To the degree that capital improvements in the nation's test facilities are required to maintain the country's leadership and/or competitive position in aeronautics, the new agency would serve as the

focal point for communicating the necessary requirements to the Congress. Other Federal departments and agencies, industry, and industry associations, could provide support on an ad hoc basis.

b. Disadvantages

This option could conceivably take more than a decade to develop, authorize, and implement. In the absence of adequate support from the affected Federal departments and agencies, the Office of Management and Budget, the U.S. aerospace industry, or any given presidential administration, it is subject to failure.

c. Discussion

In considering this option, Government decision-makers must take the risk of failure into account. This option is not a substitute for short-term action designed to maintain large-scale subsonic wind tunnel testing capability in the United States. Rather, it is a long-term solution to (1) the difficulties of coordinating efforts across agency lines and (2) the complexity of budgeting and funding for aeronautical test facilities. The circumstances of the latter call upon one Federal agency to provide robust support to another in the absence of assurance that adequate resources will be available to defray the costs of operating and maintaining those facilities without adverse effects on the owning agency's other missions.

d. Conclusion

If senior management in the DoD finds this long-range option to be desirable, it would be appropriate to first select one of the top seven of the eight prioritized alternatives and proceed with implementation. That way, the immediate challenge of responding to NASA's inactivation of the subsonic wind tunnels at the Ames Research Center will have been met with at least a short-term response that provides DoD components and supporting U.S. aerospace industry with a means of continuing to conduct large-scale subsonic wind tunnel testing. Then, the requisite network of appropriate subject matter experts from the affected activities can be established to develop a comprehensive strategy for the pursuit of the long-term solution.

2. Option 2—Transfer Ownership and/or Operation to a Non-Federal Entity

This long-range option involves transferring ownership and/or operational responsibility for the inactivated subsonic wind tunnels at the Ames Research

Center to a non-Federal organization. The transferee might be a private corporation, a university, or a consortium of businesses and academic institutions. If possible, the transfer should provide for Federal entities such as the DoD, NASA, and the Federal Aviation Administration, as well as the supporting U.S. aerospace industry, to have priority in the use of these aeronautical test facilities.

a. Advantages

This option would relieve the Federal Government of the responsibility for the requisite funding for capital investments and the core operating costs to keep unique national aeronautical test facilities operating. If it is possible for those test facilities to be self-sustaining, entrepreneurs would be afforded the opportunity to manage the facilities as a business enterprise. The transferee may be able to use other financial resources to supplement revenues obtained from customers. Successful implementation of this option could keep unique test facilities open and available to customers in the DoD and the supporting U.S. aerospace industry.

b. Disadvantages

It could take several years to find a suitable organization to assume ownership or operation of the inactivated subsonic wind tunnels and complete the necessary legal processes for a transfer of ownership or operational responsibility. In the interim, the facilities are subject to deterioration because they would not be in use, and adequate resources may no longer be available for their maintenance. During that time, they might deteriorate to the point where they are beyond economical recovery. Similarly, if the Federal Government were to relinquish its control over the facilities, and the organization taking control were unable to operate the facilities on a self-sustaining basis, they could be expected to deteriorate to the point where demolition would be likely to follow.

c. Discussion

In considering this option, Government decision-makers must take the risk of failure into account. Short-term action designed to maintain large-scale subsonic wind tunnel testing capability in the United States would probably still be necessary. This option offers a risky long-term solution in which the Federal Government would be abandoning its investment in unique aeronautical test facilities as well as its ability to control their destiny in the future.

The DoD has the principal need, and should be the primary customer, for these facilities. Either directly or indirectly, the DoD will support the cost of operation, maintenance, and improvement of the wind tunnels. Even when aerospace companies appear to put their own money into test facilities, most of those funds are reimbursed as allowable overhead on Government contracts.

The cost of keeping these large wind tunnels operational appears beyond the resource capability of universities or perhaps any aerospace company. Worldwide, such expensive testing facilities are owned and supported by national governments. All major test facilities in the United States were funded, and are operated, on that concept.

Implementation of this long-term option would require action by NASA. Hence, pursuit of this option by senior managers in the DoD would entail persuading NASA officials that the option had sufficient merit for them to give it serious consideration.

d. Conclusion

If senior management in the DoD finds this long-range option to be desirable, it would still be appropriate to first select one of the top seven of the eight prioritized alternatives and proceed with implementation. That way, the immediate challenge of responding to NASA's inactivation of the subsonic wind tunnels at the Ames Research Center will have been met with at least a short-term response that provides the DoD components and the supporting U.S. aerospace industry with a means of continuing to conduct large-scale subsonic wind tunnel testing. Then, the tasks of persuading NASA officials to pursue this course of action, identifying an appropriate transferee and formalizing the transfer of ownership and responsibility could be pursued in due course.

X. Findings, Conclusions, and Recommendations

The announcement that NASA is inactivating the two largest wind tunnels in the world as well as the 12-Foot Pressure Wind Tunnel is significant to both the Department of Defense and the U.S. aerospace industry. The two large wind tunnels in the NFAC are unique national assets, and the 12-Foot Pressure Wind Tunnel was recently renovated. Since virtually any new aircraft or missile will operate in the subsonic flight regime at least during periods of take-off and landing, the capability to perform wind tunnel tests at subsonic speeds is important. Generally, the larger the model that can be tested in a wind tunnel, the more accurately the test results will reflect flight conditions. The facilities that NASA has chosen to close have continued life expectancy, and their premature closure not only forces DoD components and U.S. aerospace companies to pursue other alternatives, it denies the U.S. Government a full return on its capital investment as well. The decision to require these wind tunnels and other NASA test facilities to be self-sustaining through the recovery of fully burdened operating costs has far-reaching implications for the Federal Government and the nation.

We found that, even with interagency agreements in place, the organizations they established were ineffective in preventing what amounted to a unilateral NASA decision to close three subsonic wind tunnels on which the DoD had come to rely.

A. Findings

This section summarizes the principal findings from this study.

1. NASA's Decision to Close the Facilities

We inquired into why NASA made the decision to inactivate the NFAC and the 12-Foot Pressure Wind Tunnel at the Ames Research Center. Several conditions converged that cumulatively resulted in the underutilization and inactivation of those facilities. In recent history, there have been fewer "new starts" in aircraft development. The number of defense contracts that require large/full-scale wind tunnel testing has also declined. Mergers and consolidations have reduced the number of defense contractors, and particularly when the

NFAC and the 12-Foot Pressure Tunnel were closed for extended periods of time for repair or renovation, some DoD components and U.S. aerospace companies elected to have their wind tunnel testing performed at alternative facilities, some outside the United States.

Advances in computational fluid dynamics obviated the need for some wind tunnel testing. NASA's funding for aeronautics has progressively declined. NASA budgets have reduced funding for rotorcraft research, leaving NASA's primary partner in this area, the U.S. Army, without sufficient resources to compensate for the NASA share.

Last, but not least, NASA began a full-cost accounting effort in 1995, and it will be fully implemented in fiscal year 2004. That initiative includes a policy that requires NASA centers to recover the full cost of operating and maintaining their test facilities from the customers of those facilities. Customer costs increased as NASA added various cost elements to customer rates, and those price increases have caused some customers to move their programs out of either the NFAC or the 12-Foot Pressure Wind Tunnel. In public announcements, NASA indicated that the two facilities are simply not generating enough testing revenue to operate on a self-sustaining basis.

2. Full-Cost Recovery and Declining Use of Tunnel at Ames

We explored the hypothesis that there was a strong positive correlation between implementation of NASA's full-cost recovery policy and declining use of the recently inactivated wind tunnels.

With respect to the NFAC, there was no regular pattern of diminishing use over time that corresponded to the phased implementation of full-cost recovery. There was one important case of a critical JSF test withdrawing largely because of full-cost recovery, and there was strong evidence that full-cost recovery adversely affected the ability of the Army to conduct its rotorcraft research.

Declining utilization of the 12-Foot Pressure Wind Tunnel was complicated by the fact that some major customers of that tunnel, to include Boeing and the Naval Air Systems Command (NAVAIR) were disappointed that, when the tunnel was renovated in the 1990s, it was not upgraded to include features that their personnel had recommended. The most fundamental issues were the fact that NASA used a circular cross section and smaller test section than personnel at Boeing and NAVAIR considered appropriate. Boeing took most of its testing for fixed-wing aircraft to England, where the company had already spent nearly a decade developing a flight database on its aircraft by the time the 12-Foot Pressure Wind Tunnel reopened. Boeing had reached a point where it would be

difficult and expensive to start over in a new wind tunnel. NAVAIR also saw some of its wind tunnel testing work go to foreign wind tunnels. Furthermore, one of NAVAIR's biggest development projects, the Joint Strike Fighter, is an international engineering and manufacturing development effort, and several foreign partners are making wind tunnel testing part of their contribution.

Considering the many influencing variables and the evidence available, we could not conclude whether or not there was a strong positive correlation between NASA's phased implementation of full-cost recovery and declining use of the subsonic wind tunnels that have recently been inactivated. On the other hand, we can conclude that full-cost recovery was a contributing factor in the ultimate loss of workload that led to the inactivation of the NFAC. It represents a departure from policies that were in effect for decades allowing Federal Government activities to conduct tests in NASA wind tunnels without charge. It appears to violate a provision of the Code of Federal Regulations that precludes NASA from charging industry for projects that are either under contract with, or supported by a letter of intent from, a Government agency.³⁷ The policy also seems to be inconsistent with NASA's Financial Management Manual, which provides that, for agreements made under the Unitary Wind Tunnel Act of 1949, NASA does not charge other Federal agencies and that it does not charge depreciation or overhead costs to non-Federal agencies.

3. Use of Foreign Tunnels

The closure of the NFAC and the 12-Foot Pressure Wind Tunnel, combined with the continued application of fully burdened costs to customers of NASA's aeronautical test facilities, could be very harmful to the DoD and the supporting U.S. aerospace industry, with a disproportionately deleterious effect on the U.S. rotorcraft industry. We found that a substantial amount of wind tunnel testing work is already being conducted outside the United States. If the prices resulting from implementation of the full-cost recovery policy contribute to declining use of other NASA wind tunnels, the expected result is that even more wind tunnel testing, to include testing in other flight regimes, will migrate to foreign wind tunnels.

There are multiple reasons that U.S. aerospace companies and DoD components are choosing to have wind tunnel tests conducted in foreign wind tunnels. Tests for the JSF are being performed in several countries because it is a large international effort and nine countries are participating in the engineering

³⁷ NASA is attempting to update the Code of Federal Regulations.

and manufacturing development phase. Testing for the T-45, which is a derivative of the British Hawk, was conducted in England because a large-scale model of the aircraft had already been tested there and the manufacturer was comfortable testing a modified model in the same tunnel to get to a full-scale Reynolds number. The P-3C was tested in Canada because the Canadians had the capability to test powered motors on propellers at the time, and NASA did not. Similarly, NAVAIR's plans to conduct powered tests of propellers on the E-2C at high pressure are likely to result in testing in either Switzerland or France, where the capability exists to perform those tests with experienced personnel.

Sometimes, the reason for use of a foreign wind tunnel is simply value. Boeing personnel emphasize the importance of cost per data point. They prefer the productivity of European wind tunnels, where the run rates are higher and the staffs are larger. Models can be built in test preparation areas and brought into the test section solely for testing rather than building and modifying models in the test section itself. Boeing personnel also prefer QinetiQ's 5-meter tunnel in England to NASA's 12-Foot Pressure Wind Tunnel because the NASA tunnel's smaller size and higher pressures make it necessary to use oversize brackets to secure an aircraft model, with a resulting adverse effect on aerodynamics and measurement. Although security of data and models in foreign tunnels is always a concern, U.S. customers seem to be gaining increased confidence in the protection of their data in selected foreign wind tunnels.

B. Conclusions—Alternatives and Options for the DoD

One logical consequence of the foregoing findings is that, absent some action on the part of the Department of Defense to change the course of events, it is foreseeable that the congressional objectives that were articulated during the Truman Administration will no longer be sustained. One of those objectives was attaining and maintaining a position of aeronautical pre-eminence in the world. Another was that wind tunnels that are maintained and staffed by the organization that is now NASA would be available to meet industry's requirements to test experimental models of new aircraft and missiles. Subsonic wind tunnel testing will continue to be conducted abroad, testing in other flight regimes may soon follow, and U.S. aerospace companies could continue to lose market share to foreign competitors in the areas of military, commercial, and dual-use aircraft because the United States is no longer at the cutting edge of aeronautical research and development.

We prioritized eight alternatives in Chapter IX of this report, and we included two long-range options for consideration. We clearly prefer the first

three alternatives over the others. We assigned maintenance of the status quo the least priority, largely because of the considerations outlined in the previous paragraph. The alternatives are the subject of our first recommendation below. For convenience, a summary of the alternatives presented in Chapter IX is repeated in Table 2.

Table 2. Summary of Alternatives and Options

Number	Description
<i>Alternatives (prioritized)</i>	
1	Assume ownership of or lease the NFAC (and possibly the 12-Foot Pressure Wind Tunnel), assume operational responsibility, and upgrade the facilities to meet current and future needs.
2	Prevail upon NASA to continue to maintain and, as necessary, operate the large/full-scale subsonic wind tunnels (and possibly the 12-Foot Pressure Wind Tunnel) at the Ames Research Center.
3	Assume ownership of or lease the NFAC (and possibly the 12-Foot Pressure Wind Tunnel) and assume operational responsibility without upgrading or modifying the facilities.
4	Construct state-of-the-art subsonic wind tunnels using Military Construction Appropriations to restore national testing capability.
5	Use alternative wind tunnels in the United States.
6	Conduct large/full-scale subsonic testing in foreign wind tunnels.
7	Increase reliance on computational modeling and simulation in lieu of wind tunnel testing
8	Maintain the status quo
<i>Options (not prioritized)</i>	
1	Establish an independent agency with ownership and operational responsibility for major U.S. aerospace test facilities.
2	Privatize the inactivated subsonic wind tunnels or transfer operational responsibility to a non-Federal organization.

C. Recommendations

This section presents our recommendations.

1. Implement One of the High-Priority Alternatives in this Study

We recommend that the Office of the Secretary of Defense select one of the top three alternatives in Chapter IX and begin implementation of that alternative as soon as practicable. Chapter IX of this study explores the consequences of failing to take action or adopting a low-priority alternative.

2. Formalize a Forecasting Process for DoD Use of NASA Aeronautical Test Facilities

We recommend that the Office of the Secretary of Defense develop a formal process to periodically validate the requirements that the respective DoD components have for the use of NASA aeronautical test facilities and share those forecasts with NASA sufficiently in advance to allow NASA to provide for those requirements in its test scheduling and its budgetary process. The new system should be an improved, more comprehensive system than those that have been used in the past, and the DoD should be faithful to seeing it accomplished.

3. Review Policies and Practices Regarding International Cooperation in Test and Evaluation Programs

The concept paper in Appendix G reflects a partnership arrangement under which the United States would exchange test-related information with foreign countries. We note in Chapter VII that DoD components and the U.S. aerospace industry are at risk of becoming increasingly dependent upon foreign wind tunnels for aeronautical testing. We also note that some representatives of DoD components and some U.S. aerospace companies have concerns about the security of their data and models when using foreign wind tunnels. The Office of the Secretary of Defense is encouraging international cooperation in test and evaluation.

Consequently, we recommend that the Office of the Secretary of Defense review its policies and practices with respect to international cooperation in test and evaluation matters to ensure that the security of test data and models is adequately protected in terms of industrial security as well as national security. Policies and practices must also ensure that increased dependence on foreign facilities over which U.S. entities have no control is consistent with national objectives regarding aerospace technological superiority.

4. Ascertain the Utility, Value, and Enforceability of Existing Interagency Memoranda of Agreement between NASA and the DoD

Chapter IV contains a discussion of the efficacy of existing alliances between NASA and the DoD with respect to major test facilities. Although that chapter concentrates on the shortcomings of those alliances and the underlying memoranda of agreement on which they are based relative to the issue of closing the subsonic wind tunnels and the Ames Research Center, we recommend that the Office of the Secretary of Defense conduct a more comprehensive review of those alliances and memoranda of agreement. The review should address the usefulness of the arrangements, whether it is cost-effective for those arrangements to continue, and whether the signed agreements are enforceable. As an element of the review, we recommend that the DoD General Counsel be asked to address the issue of the enforceability of the agreements between the DoD and NASA.

5. Assess the Complete Effect of NASA's Full Cost Recovery Policy

Chapter V discusses the specific issue of whether or not there was a direct cause-and-effect relationship between NASA's implementation of a full-cost-recovery policy and declining use of the subsonic wind tunnels at the Ames Research Center. While we could not conclude that NASA's implementation of a full-cost-recovery policy was the sole cause of the closure of the subsonic wind tunnels, we found it to be a contributing factor. We also found that it is now likely to be a sufficient deterrent to further use to ensure that the subsonic wind tunnels are not reactivated.

Consequently, it is important for the DoD to make an assessment of whether the complete implementation of the full-cost-recovery policy by all NASA centers effective in fiscal year 2004 is likely to lead to the closure of additional aeronautical test facilities (i.e., wind tunnels in other flight regimes or specialized test facilities) at the NASA research centers. Other NASA aeronautical test facilities may not be able to operate on a self-sustaining basis when their customers are charged fully burdened rates. Consequently, we recommend that the Office of the Secretary of Defense conduct a comprehensive assessment of the potential effect of NASA's implementation of its full-cost-recovery policy. That assessment should include the effects on DoD programs as well as on the budgets of the affected DoD components.

6. Ascertain Whether Application of Full-Cost Recovery to Government Projects Violates the Code of Federal Regulations

Chapter V identifies an apparent inconsistency between Section 1210.2 of Title 14 of the Code of Federal Regulations and the application of the full-cost-recovery policy to projects supported by a Government agency. Subsection 1210.2(b) states that no fee will be charged for Government projects.

We recommend that the DoD General Counsel review Section 1210, Title 14, of the Code of Federal Regulations to determine if it applies to wind tunnel testing conducted by industry with Government support. If it is applicable to such situations, and it is inappropriate for NASA to charge Government contractors fees for testing, the Office of the Secretary of Defense should so advise NASA, at the appropriate level, and request that an exception be made to the full-cost-recovery policy to bring it into compliance with the Code of Federal Regulations.³⁸

³⁸ As previously noted, NASA is attempting to update the Code of Federal Regulations.

Appendix A. **List of Principal Persons Contacted**

The IDA study team discussed the subject matter of this report with subject matter experts and senior managers in both the public and private sectors. The following list identifies the principal persons who contributed to the development of this report during those discussions. However, it is not a list of all those who were contacted in conjunction with this study or who otherwise contributed to the study effort.

U.S. Government

Office of the Secretary of Defense

Henry Sodano, Director of Military Construction, Office of the Under Secretary of Defense (Comptroller)

Andre Pugin, International Cooperation, Office of the Under Secretary of Defense (Acquisition, Technology and Logistics)

U.S. Army

David Wildes, Office of the Assistant Secretary of the Army (Acquisition, Logistics and Technology)

Barry Basket, U.S. Army Aviation and Missile Command

Andrew Kerr, Director, Aeroflightdynamics Directorate, Ames Research Center

U.S. Navy

Donald McErlean, Deputy Commander for Engineering, Naval Air Systems Command

Thomas Rudowsky, Naval Air Systems Command

Douglas Bollman, Naval Air Systems Command

John T. Lawrence, Naval Air Systems Command

Hugo Gonzales, Naval Air Systems Command
Robert P. Hay, Naval Air Systems Command
Marjorie Draper-Donley, Naval Air Systems Command

U.S. Air Force

David Bond, Air Force Materiel Command (HQ AFMC/DOX)
Howard Lebovitz, Air Force Materiel Command (HQ AFMC/DOX)
Keith Kushman, Arnold Engineering Development Center
Carlos Tirres, Arnold Engineering Development Center
David M. Hiebert, Arnold Engineering Development Center

NASA Headquarters

Blair Gloss, NASA Facility Group Director
Owen Barwell, Financial Management
Howard Kwok, Office of Inspector General

NASA, Ames Research Center

Steven F. Zornetzer, Deputy Center Director
Lewis Braxton, Chief Financial Officer
George Kidwell, Deputy Director, R&D Services Directorate
Michael George, Chief, Wind Tunnel Operations Division
Dan Bufton, Deputy Chief, Wind Tunnel Operations Division
David Banducci, Wind Tunnel Operations Division
Frank Kmak, Chief, Wind Tunnel Operations Branch

U.S. Industry/Associations

Allied Aerospace Industries, Incorporated

Lowell C. Keel

American Helicopter Society, International

M. E. Rhett Flater, Executive Director

Bell Helicopter Textron

Walter Sonneborn, Former Vice President

Robert Mullins, Jr., Chief, Research and Technology Development

John Sherrer, Director of Research

Warren Young, Chief of Research

Tom Wood, Chief, Preliminary Design

Bihrlle Applied Research, Inc

Billy Barnhart, Vice President

Boeing Company

Conrad Ball, Director, Enterprise Laboratories and Test Technologies
(Phantom Works)

Donald Hallock, Wind Tunnel Center of Excellence

Kevin Mejia, Lead Engineer, Testing Methods and Technology (Commercial Airplanes)

Stephen Northcraft, Aerodynamics Technology

Brian Nield, Aerodynamics Engineering (New Airplane Product Development)

John Shaw, Chief Scientist, Boeing Rotorcraft

Jacobs-Sverdup Technologies

Wayne Hawkins, AEDC Group

Frank W. Steinle, Jr., AEDC Group

Lockheed Martin Company

Mark Melanson

Rob Burchak

RAND

Phillip Anton

Consultant

Melvin A. Luter (Naval Air Systems Command, retired)

U.K. Industry**Aircraft Research Association, Ltd.**

Marylyn Wood, Business Development Manager

Appendix B.

Memorandum of Agreement between the DoD and NASA

**MEMORANDUM OF AGREEMENT
BETWEEN
THE DEPARTMENT OF DEFENSE
AND
THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
FOR THE
AERONAUTICS AND ASTRONAUTICS COORDINATING BOARD**

(This Agreement supersedes the previous agreement dated
September 20, 1988)

I. BACKGROUND:

The Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA) are often partners and customers of each other's capabilities in aerospace technology development and space operations. Other aspects of the DOD/NASA relationship stem from the agencies' respective interests in many of the same functional areas.

It is essential that all aeronautics and space activities which are of mutual interest to the DOD and NASA be appropriately coordinated. Where policy and program approval issues are not involved, this coordination should be conducted by officials directly responsible for program implementation. Where policy and program approval issues are involved, the exchange of information, the planning and coordination of activities, and the resolution of problems should be conducted by senior management officials having the authority to make decisions and direct their implementation within their respective organizations.

II. PURPOSE:

This agreement establishes the Aeronautics and Astronautics Coordinating Board (AACB) as the senior management review and advisory body internal to the DOD and NASA to facilitate coordination of aeronautics and space activities of mutual interest. Its organization and principles of operation are prescribed.

III. AUTHORITY:

This agreement is entered into in furtherance of the purpose of the National Aeronautics and Space Act of 1958, as amended, (42 U.S.C. 2451, et seq.).

IV. ORGANIZATION:

The Under Secretary of Defense (Acquisition and Technology) and the NASA Deputy Administrator will cochair the Board.

Other Board members are -

for DOD:

Director, Defense Research and Engineering
Deputy Under Secretary of Defense (Space)
Assistant Secretary of the Air Force (Acquisition)
Assistant Secretary of the Navy (Research, Development & Acquisition)
Assistant Secretary of the Army (Research, Development & Acquisition)
Assistant Secretary of the Air Force (Space)/Director,
National Reconnaissance Office

for NASA:

Associate Deputy Administrator (Technology)
Associate Administrator for External Relations
Associate Administrator for Space Flight
Associate Administrator for Space Communications
Associate Administrator for Aeronautics
Associate Administrator for Space Science
Associate Administrator for Space Access and Technology
Associate Administrator for Mission to Planet Earth

Each cochair shall designate an executive secretary directly responsible to him/her for administrative support of the Board's activities. For the DOD, the executive secretary shall be provided by the Deputy Under Secretary of Defense (Space); for NASA, by the Director, Defense Affairs Division. For the purpose of executive sessions, the executive secretaries shall be considered Board members.

Full use shall be made of existing facilities and capabilities. Staff support may be drawn from other elements of the DOD and NASA.

Panels to address aeronautics, space launch systems, spacecraft, and space operations shall be established by the Board. Additional Panels may be established for other functional areas to facilitate considerations by the Board.

Ad hoc Panels may be established for special purposes such as to address temporal topics crosscutting functional areas of other Panels. Panels shall be cochaired by DOD and NASA senior managers.

Panels are responsible for identifying and maintaining awareness of activities of mutual interest within their respective functional areas. When topics requiring special attention are identified, they will be assigned by the Board cochairs to Panels for review and recommendation. Panels shall establish Working Groups tailored to address specific issues referred by the Board. Terms of Reference and tasking for each Panel shall be approved by the cochairs of the Board.

Cochairs of the Panels will be appointed by the cochairs of the Board. Other Panel members and Working Group members will be appointed by their Panel cochairs. Panel and Working Group members shall be comprised exclusively of full-time government employees.

V. PRINCIPLES OF OPERATION:

The Board shall meet at least annually to receive summary reports from the Panels and, at the call of the Board cochairs, to address special issues.

The Board cochairs shall alternately preside over meetings. Each cochair will normally host those meetings over which he/she presides.

Only Board members, and such others as the Board cochairs specifically approve, may attend meetings.

Actions based on consideration of matters and recommendations by the Board may be taken by individual members through authority otherwise vested by virtue of their positions within their respective organizations.

Issues not resolved by the Board may be referred to the Deputy Secretary of Defense and the NASA Administrator for resolution.

The Board, through its executive secretaries, shall establish its own administrative procedures.

VI. IMPLEMENTATION:

This Agreement is effective on the date of the last signature hereon and shall remain in effect until terminated by either party through written notice to the other party.

FOR THE DEPARTMENT OF DEFENSE:

William J. Perry

William J. Perry
Deputy Secretary of Defense

Date: 5 Nov 93

FOR THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION:

Daniel S. Goldin

Daniel S. Goldin
Administrator

Date: 10/29/93

ADMINISTRATIVE CHANGE:

This memorandum of agreement has been modified, effective August 15, 1995, to reflect fact-of-life functional realignments and changes in organizational designations current as of that date.

Appendix C.

Large-Scale Wind Tunnels with Subsonic Test Capabilities

Table C-1 lists selected subsonic wind tunnels located in Canada and Western Europe that might be suitable for the type of wind tunnel testing required by DoD components or supporting elements of the U.S. aerospace industry. The three wind tunnels that have recently been inactivated at NASA's Ames Research Center are included at the beginning of the table for purposes of comparison.

Table C-1. Selected International Subsonic Wind Tunnels

Name	Location	Facility	Size (Feet)	Length (Feet)	Speed/ Mach	Status	Comment	Year Built	Reynolds # X106
NASA—Ames Research Center, 80 × 120 Low-Speed Wind Tunnel	Moffett Field, Mountain View, California	80×120 Subsonic Wind Tunnel	80×120	190	0-0.2	Inactive	Closed circuit, acoustic	1982	1.1
NASA—Ames Research Center, 40 × 80 Low-Speed Wind Tunnel	Moffett Field, Mountain View, California	40×80 Subsonic Wind Tunnel	40×80	80	0-0.45	Inactive	Closed circuit, acoustic	1944; 1982 upgrade	3
NASA—Ames Research Center, 12-Foot Pressure Wind Tunnel	Moffett Field, Mountain View, California	12-Foot Pressure Wind Tunnel	12-ft. diameter	28	0.05-0.55	Inactive	Closed return, solid wall	1946; 1994 Restoration	9
German-Dutch Wind Tunnels, NOP Business Unit LLF	Marknesse, Netherlands	LLF 6×6m Large, Low-Speed Facility	19.7×19.7	49	0 - 0.44	Active	Closed or slotted walls; Atmospheric Pressure	1980	6
German-Dutch Wind Tunnels, NOP Business Unit LLF	Marknesse, Netherlands	LLF 8×6m Large, Low-Speed Facility	22.6×19.7	65	0 - 0.34	Active	Closed or slotted walls; Atmospheric Pressure	1980	5.3
German-Dutch Wind Tunnels, NOP Business Unit LLF	Marknesse, Netherlands	LLF 8m×6m Large, Low-Speed Facility	22.6×19.7	61	0 - 0.25	Active	Open Jet; Atmospheric Pressure	1980	3.9
German-Dutch Wind Tunnels, NOP Business Unit LLF	Marknesse, Netherlands	LLF 9.5×9.5m Large, Low-Speed Facility	31.1×31.1	65	0 - 0.18	Active	Closed Walls; Atmospheric Pressure	1980	3.9
German-Dutch Wind Tunnels, NOP Business Unit LST	Marknesse, Netherlands	LST Low-Speed Tunnel	9.8×7.4	29 (total); 19 (aero- nautical)	0 - 0.23	Active	Closed walls	1983	1.4
Institute for Aerospace Research, Low-Speed Wind Tunnel	Ottawa, Canada	NRC (National Research Council) 9m Low-Speed Wind Tunnel	30 × 30	79	Up to 180 ft/sec	Active	Closed circuit, Atmospheric pressure test section	1970; Being revamped	3.6

(Continued on the next page.)

Table C-1—Continued

Name	Location	Facility	Size (Feet)	Length (Feet)	Speed/Mach	Status	Comment	Year Built	Reynolds # X106
ONERA, F1	Le-Fauga-Mauzac, France	F1 Wind Tunnel	14.8×11.5	36	123 m/sec. or 403 ft/sec	Pressurized wind tunnel continuous		1977	8
ONERA, F2	Le-Fauga-Mauzac, France	F2 Wind Tunnel	4.6×5.9	16	0 - 100 m/sec.	Active	Atmospheric continuous	1983	1.1
ONERA, S1MA	Modane-Avrieux, France	S1MA Subsonic Wind Tunnel	26-ft. diameter	25	< Mach 1	Active	3 interchangeable test sections (slotted/solid/anechoic walls)	1951	7.3/7.9
TsAGI, T101	Zhukovsky, Russia	T101 Subsonic Wind Tunnel	78.7×45.9 (Elliptical)	79	5 - 55 m/sec	Active	Full scale wind tunnel w/open test section	1939; modifications in 1978 and 1991	3.3
RUAG Aerospace, Large Subsonic Wind Tunnel	Emmen, Switzerland	7×5 Meter Low Speed Tunnel (LWTE)	23×16.4	49	68 m/sec	Active	Atmospheric. Closed circuit	1945; modifications in 1982, 1987, 1992, and 1995	4.5
QinetiQ, 5-Meter Low-Speed Wind Tunnel	Farnborough, England, UK	5-Meter Low-Speed Wind Tunnel	13×16	26	.05 to .34 Mach	Active	Closed Return	1977; continually improving	7.6

Appendix D.

Interagency Agreement between NASA and the DoD to Establish NATA

**National Aeronautical Test Alliance
Interagency Agreement Between
The National Aeronautics and Space Administration
and
United States Department of Defense**

I. Introduction

This Interagency Agreement (IAG) is entered into by the National Aeronautics and Space Administration (NASA) and the United States Department of Defense (DoD) (the "Parties") to establish a National Aeronautical Test Alliance (NATA).

II. Purpose

The purpose of the NATA is to facilitate the establishment of an integrated national strategy for management of their aeronautical test facilities. The objective of NATA is to provide a forum for DoD and NASA to consult on the integration of the management of aerodynamic, aerothermodynamic, and aeropropulsion facilities owned or operated by the United States, taking into account military, civilian, and commercial aerospace interests, to the extent permitted by law.

III. Background

In 1995, the U.S. President's National Science and Technology Council issued a report entitled, "Goals for a National Partnership in Aeronautics Research and Technology" which indicated that "newer European wind tunnels focused on aircraft development testing are generally superior to comparable U.S. facilities in overall capability." As a consequence, there has been increasing utilization of European facilities for U.S. commercial and military aircraft development testing. NASA and DoD share several concerns regarding this practice, including facilities access and data security risks. There have been a number of studies addressing these issues, *i.e., the National Facility Study (1993), the NASA/DoD Cooperation Study (1996), and the DoD Aeronautical Test Facilities Assessment Study (1997)*. In early 1998, NASA and DoD established a National Wind Tunnel Alliance (NWTA) and an Air Breathing Propulsion Test Facilities Alliance (ABPTFA), under the auspices of the Aeronautics and Astronautics Coordinating Board (AACB), to identify, study, and implement measures to strengthen the national infrastructure of aerodynamic and air breathing propulsion test facilities that support NASA and DoD missions, and the domestic aeronautics industry. NASA and DoD have now determined that the NWTA and ABPTFA approaches should be expanded upon to address the above concerns.

IV. Terms of Agreement

- A. NASA and DoD agree to establish and support the NATA, as a team approach to be used as outlined in this IAG.**
- B. The NATA shall serve as a forum for coordinating NASA and DoD policy pertaining to such facilities and making recommendations, as appropriate, relevant to the use and management of such facilities to NASA and DoD management. Each agency agrees that it shall actively participate in the NATA on matters pertaining to such Government-owned test facilities. DoD issues will be coordinated through the Test and Evaluation Board of Directors Executive Agent prior to review by the Defense Test and Training Steering Group (DTTSG).**
- C. NASA and DoD further agree to provide the necessary resources to support the objectives of the NATA, consistent with applicable law. Such resources may include, but not be limited to, personnel, equipment, supplies, and facilities.**
- D. NASA and DoD shall individually retain their respective exclusive responsibilities and authority, direction and control over the following:**
 - Real and tangible property, including equipment, located within their respective installations.**
 - 2. Oversight of NATA activities.**
 - 3. Funding for their participation on the NATA, consistent with applicable law.**
 - 4. Personnel. To the extent that personnel are assigned to work full-time on NATA-related topics, the assigning party agrees to accept input from the other Party for consideration in conducting annual performance appraisals.**

V. Facilities

Designated test facilities within the purview of NATA are located at four installations within the continental United States: Ames Research Center (ARC), Arnold Engineering Development Center (AEDC), Langley Research Center (LaRC), and Glenn Research Center (GRC). The specific test facilities that fall under the managerial purview of NATA are identified by name and location in Appendix A of this IAG.

VI. Organization and Funding

The Parties agree that this IAG does not establish any new organizations and that it is not a funding document. NASA and DoD shall each provide support to the NATA from within their own agencies and shall fund their own participation on the NATA. The requirements of this IAG are subject to the availability of appropriated funds and no provision in this IAG shall be

construed as a commitment to provide resources in violation of the Anti-Deficiency Act, 31 U.S.C. 1341 et seq. or any other applicable statute or regulation.

Executive Agents

The Secretary of the Air Force or designee shall serve as the DoD Executive Agent for implementation of this agreement within DoD. The NASA Associate Administrator of Aero-Space Technology or designee shall serve as the NASA Executive Agent for implementation of this agreement within NASA. The Executive agents shall implement the terms of this agreement, consistent with applicable law.

VIII. Modifications

This IAG may be modified by written agreement of the Parties signing below, or their designees.

Termination

This IAG may be terminated by either Party upon 30 day written notice to the other Party.

X Effective Date and Term

This IAG becomes effective on the date it is finally signed by both Parties and shall expire five (5) years thereafter, unless otherwise terminated in accordance with section IX. This IAG may also be renewed at the end of the applicable term by mutual written agreement of the Parties or their designees.

Execution

National Aeronautics and Space Administration

By: Daniel R. M I
Associate Deputy

Date: JUN 5, 2000

Department of Defense

By: Randy B. Sager
Deputy Secretary of Defense

Date MAY 12 2000

Appendix A
NATA Facilities

Facility	Location
12-Ft. Pressure Wind Tunnel	ARC
Unitary Plan Wind Tunnels (11 Ft., 9x7 Ft., 8x7 Ft.)	ARC
National Full Scale Aerodynamic Complex (40x80 Ft., 80x 120 Ft.)	ARC
National Transonic Facility	LaRC
14x22 Ft. Wind Tunnel	LaRC
Transonic Dynamics Tunnel	LaRC
Unitary Pan Wind Tunnel (Both test sections)	LaRC
16 Ft. Transonic Tunnel	LaRC
20 Ft. Vertical Spin Tunnel	LaRC
20 In. Supersonic Wind Tunnel	LaRC
Low Turbulence Pressure Tunnel	LaRC
0.3 Meter Cryogenic Tunnel	LaRC
8 Ft. High Temperature Tunnel	LaRC
20 In. M6 Hypersonic Tunnel	LaRC
20 In. M6 CF4 Tunnel	LaRC
31 In. M10 Tunnel and 5 In. M6 HTT	LaRC
22 In. M20 Hypersonic Tunnel	LaRC
Icing Research Tunnel	GRC
8x6/9x15 Tunnels	GRC
Unitary Plan Tunnel (10x10 Supersonic)	GRC
Test Cells (PSL-3, PSL-4, and ECRL-2B)	GRC
Hypersonic Test Facility	GRC
16T/16S	AEDC
4T	AEDC
Aerodynamic Propulsion Test Unit (APTU)	AEDC
Test Cells C-1 and C-2	AEDC
Test Cells T-1, T-2, T-4 and T-5	AEDC
Test Cells J-1, J-2	AEDC
Test Cells T-11, T-12, SL-1, SL-2	AEDC
Von Karman Facilities	AEDC
Tunnel 9 Nitrogen	AEDC

Appendix E.

Projected Occupancy Hours at Ames Wind Tunnels

Table E-1. Ames Wind Tunnel User Occupancy Hours

	Fiscal Year					
	1997	1998	1999	2000	2001	2002
Unitary Plan Wind Tunnel						
Projected Hours	*	*	*	*	3,040	2,656
Actual Hours	*	*	*	*	2,201	1,146
Percentage Actual (Actual ÷ Projected)	NA	NA	NA	NA	72.4%	43.1%
12 Foot Wind Tunnel						
Projected Hours	2,912	2,912	1,552	160	160	80
Actual Hours	1,870	3,000	1,582	119	120	54
Percentage Actual (Actual ÷ Projected)	64.2%	103.0%	101.9%	74.4%	75.0%	67.5%
National Full-Scale Aerodynamic Complex						
Projected Hours	**	**	2,585	2,038	2,058	464
Actual Hours	**	**	1,801	1,481	2,343	197
Percentage Actual (Actual ÷ Projected)			69.7%	72.7%	113.8%	42.5%
Notes:						
* The Unitary Plan Wind Tunnel was not in operation during fiscal years 1997 through 2000 because of a facility modernization project.						
** The National Full-Scale Aerodynamic Complex was not in operation during fiscal years 1997 and 1998 because of a facility modernization project.						

Source: Reference [28], Enclosure 2.

Appendix F.

Summary of the Arnold Engineering Development Center's Effort to Implement Full-Cost Recovery

<p style="text-align: center;">DEPARTMENT OF THE AIR FORCE HEADQUARTERS ARNOLD ENGINEERING DEVELOPMENT CENTER (AFSC) ARNOLD AIR FORCE STATION, TENNESSEE 37389</p> <p>REPLY TO: CC ATTN OF: CC</p> <p>SUBJECT: Summary of AEDC Service Fund Operations, FY 1971</p> <p>TO: AFSC (CC)</p>	 <p style="text-align: right;">13 August 1971</p>
<p>1. For the past several years, AEDC has kept HQ AFSC informed of progress and problems experienced under service fund operations by making verbal and/or written quarterly progress reports. At the end of each fiscal year AEDC has submitted a report that encapsulates the high points and key issues of the year just completed. This report covers our experiences during FY 1971, and is also my final report on service funding as Commander, AEDC.</p> <p>2. FY 1971 was a difficult year under service funding at AEDC. Most of the difficulties were anticipated or predicted based upon the very uncertain market within which we had to operate, and the rules that we were obliged to follow in engaging that market, but they were still quantitatively worse than expected. A large surge of work was accomplished during the final quarter of FY 1970, both due to customer demand, and a maximum effort to earn revenue necessary to minimize the year end service fund deficit position. In spite of essentially round the clock operations, which set new records in productivity, and hindered by some last minute program dropouts, we were unable to close the gap between expenses and revenues. We closed fiscal year 1970 in a \$1.232 million deficit position. The addition of a \$129,000 carry-over deficit from FY 1969 caused us to enter FY 1971 with a cumulative service fund deficit of \$1.361 million. During FY 1971, your Headquarters funded these prior year deficits.</p> <p>3. Entering FY 1971, both your Headquarters and we recognized the inadequacies of RDT&E workload forecasting and the volatility of market predictions for this particular year. Our best estimate of workload was about \$5 million below what was deemed essential to maintain a viable capability at AEDC. Included in that best estimate was about \$10 million in major program work which was subject to significant downward swings during the process of fund authorizations and apportionments. There was an offsetting, and approximately equivalent, amount of lesser priority work not included in our best estimate which stood some chance of making during the year. After discussion, agreement was reached with Command to proceed and contract for a work program level of effort about \$5 million on the optimistic side. This level of effort required a layoff of about 12% of our contractor work force, and a 10% reduction in our Air Force staff. Of significance was a 13% increase in charge rates necessitated by the spreading of large fixed costs over a smaller operating</p>	

workload base, and a minimal AEDC line item appropriation which necessitated passing on 87% of total AEDC operating and maintenance costs to customers. Both of these factors served in a major way to discourage use of AEDC and encourage use of NASA and industrial facilities during FY 1971.

4. As the year unfolded our projected \$5 million deficit grew with the loss in workload forecast for the SST, AIM-82, and the loss or reduction of other test work. These losses were only partially offset by the fact that we were able to earn 2.8 million more than originally projected for test peculiar revenue and a half-million more in research and development revenue. Your Headquarters took action to offset this unfavorable trend. \$1.0 million was provided to the Laboratories to pay for testing at AEDC. We were also authorized to conduct needed but unfunded testing in the amount of \$2.1 million for the IFA and \$3.0 million for the Laboratories. These costs were subsequently funded and AFSC also provided \$6.7 million at the end of the year to eliminate all the remaining deficit except \$629 thousand. Total support provided by your Headquarters, either direct to AEDC or to pay for customer testing, amounted to \$12.8 million. Had this not been forthcoming, the FY 1971 deficit would have been approximately \$13.5 million, rather than the \$629 thousand actually carried forward into FY 1972. AFSC support is separately identified in the financial summary contained in paragraph 6, below.

5. While the revenue side of the service fund scale for FY 1971 was extremely volatile, the expense side of the balance equation was more accurate than ever before. This accuracy was a direct reflection of major improvements made in our accounting system since the inception of service funding. Because of this increased accuracy, we were able to impose many mutually agreed tradeoffs in effort with our contractor, resulting in significant application of total efforts to the benefit of AEDC and the Air Force, even though they were not specifically applied to revenue producing work--the demand for which did not fully materialize. Some increases in cost came in areas over which AEDC had no control. A slight increase in costs was associated with test peculiar materials paid for by customers. Civilian pay was increased by some \$65,000, and a TVA electric power rate increase of 28.5% took effect on 1 October 1970. The expected overall effect of the TVA rate increase for the year would have been \$1.150 million, but reduced test activity and close management of power distribution to avoid peak loads held this expense increase to \$369,000. Excess plant equipment and materials obtained from Mountain Home, Idaho, and Daingerfield, Texas, for use in the Aerodynamic and Propulsion Test Unit (APTU), under construction, increased transportation costs by \$56,000 more than planned. Surplus equipment value far exceeded the cost of its transportation.

6. In summary, the expense and revenue situation for FY 1971 as of year end was as indicated by the numbers below:

	<u>Original Program</u>	<u>Actual</u>	<u>Variance</u>	
<u>Expenses: (\$ x 10³)</u>				
ARO Contract	47,377	47,459		
All Other	9,000	9,505		+505
Total	56,377	56,964		+587
<u>Revenue: (\$ x 10³)</u>				
Test	46,800	30,898	(1.0)	-15,902
Test Peculiar	1,500	4,267		+2,767
Appropriated	6,827	9,178	(1.5)	+2,351
Other	1,250	1,682		
HQ AFSC Reimbursable	0	10,310	(10.3)	+10,310
Total	56,377	56,335	(12.8)*	

*Included in Actual

The net difference between expenses and revenue at year end, as stated earlier, is a \$629,000 service fund deficit. This figure was achieved only through major funding support from HQ AFSC and reflects the total cumulative AEDC service fund deficit entering FY 1972.

7. Even though FY 1971 was a bad year from a financial standpoint, it was a good year to prepare better for the future. It was a good year to learn some lessons that should help guide our way toward a better future. Let me briefly summarize:

a. FY 1971 experience made it clearly evident that the nation has more ground environmental test facilities than it can or should afford to continue to sustain at less than optimum efficient levels of operation. Effort should continue to eliminate or mothball duplicative or inferior facilities, on a national basis, and particularly those being operated largely at federal expense while serving only the vested interests of a particular industrial organization. Where federally owned and superior facilities exist which can serve a national clientele with complete objectivity and common standards for all--they should be used.

b. One of the major reasons for significant Air Force-use of NASA facilities is not simply because such use is "free," even though that is a major attraction in today's fiscal environment. Many SPDs use these facilities because NASA combines the expertise of researchers, developers, and testers all working together in common interests at one location. Location is largely dictated by the real estate and utility demands of NASA's test units which are the keystone elements around which their RDT&E efforts revolve. If we in the Air Force Systems Command are to do our specific RDT&E job better, we are going to have to combine Air Force talents through a much closer working relationship among our in-house researchers, developers, and testers than has existed during my tenure as Commander at AEDC. End item test and evaluation alone is not the answer. We frequently discover too late that technical problems exist which should have been objectively discovered and solved by adequate developmental test work long before the end item point was reached.

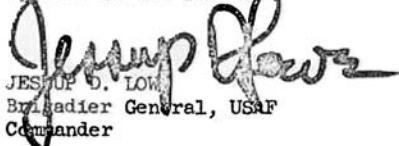
c. The demands for detailed and early expense related information are critical to service fund success. So critical, in fact, that during FY 1971 we at AEDC completed a major overhaul of a system that up until that time had been considered one of the better ones in the Command for application to service funding. Entering FY 1972 we are operating with a new system which contractually identifies 69 discrete task areas of work and 6 elements of overhead expense. Accounting and tracking of performance against these tasks and elements will be effected in accordance with the principles of the Air Force's C/SCSC system during the year. This effort should result in sufficiently early identification of unfavorable expense trends or task balances to allow better expense management throughout the course of the year.

d. Charge rate increases applied during the course of an operating year are counterproductive. Such increases simply further reduce the volume of work performed, thereby driving costs and hence rates even higher. More importantly, these rate increases discourage adequate test and evaluation, and often at times when it is needed most. We have no good way of knowing just how many technical risks have been passed along to the flight phase of on-going programs for lack of funds to do adequate ground testing at AEDC rates. We suspect that these instances are appreciable, thereby obviating the very reasons for which this Center was built.

e. If service fund operations must continue at AEDC, then at least the 60/40 split between appropriated and customer funding, finally achieved for FY 1972, should be maintained. (A 75/25 split would be even better.) A split of this sort assures enough customer funding to insure planning, marketing, programming, and cost disciplines inherent in the service fund system while at the same time not imposing costs wholly irrelevant to the program being served.

8. I leave FY 1971 and AEDC with the conviction that we are in a better position starting FY 1972 than in any of our prior years under service funding. Headquarters AFSC has done a fine job in helping us over the rough spots, particularly by providing fund support and in directing revenue producing work into AEDC. Without such support we'd have had little choice but to essentially wipe out a significant national capability that has taken since 1949 to build. We enter FY 1972 with a much firmer workload than before, a system for expense tracking and management in detail, a 40% reduction in charge rates, that is already showing positive evidence of attractiveness to customers, and a residual cumulative deficit of only \$629,000. I think there's a good chance that AEDC can achieve a break-even position under service funding in FY 1972, but this remains to be seen.

9. In conclusion, I have not yet, nor do I foresee, becoming an advocate of service funding--particularly in the test and evaluation domain. Increasing complexity of modern aerospace systems demands more and more test and evaluation and exact needs are often most difficult to specifically define or accurately forecast. Many can never be defined in time to match lengthy budgeting, appropriation, and apportionment cycles. Accordingly, I urge that test and evaluation capability be made readily and freely available to whomever and whenever it is needed with accounting for actual program costs as necessary after the fact rather than before. I sincerely feel that this, along with a closer working communion among our researchers, developers, and testers is in the best national interests and one of the key answers to better operational systems of the future.


JESSUP D. LOW
Brigadier General, USAF
Commander

Appendix G.

Concept Paper: Framework Memorandum of Understanding on Cooperative Test and Evaluation

A Cooperative Test and Evaluation Programs (TEP) Memorandum of Understanding (MOU) will:

- establish a framework for a broad range of cooperative or reciprocal Test and Evaluation (T&E) activities, including management functions;
- provide specific provisions that will enable the timely, efficient establishment of reciprocal T&E Project Agreements or Arrangements (PAs), whereby each Participant will gain access to the other Participant's T&E facilities at the other Participant's T&E preferred rates;
- provide specific provisions that will enable the timely, efficient establishment of cooperative T&E loan agreements or arrangements for loan of test instrumentation or equipment for T&E purposes;
- provide specific provisions that will enable the timely, efficient establishment of cooperative T&E projects through PAs;
- include provisions for T&E information exchange, whereby the Participants may share testing-related information (such as specifications for a piece of instrumentation/test equipment) as well as testing-related criteria, standards, and procedures;
- include provisions for familiarization visits by Participants' T&E personnel to identify potential T&E cooperative opportunities, in accordance with Participants' international visit procedures.

Scope: The scope of the MOU will cover the following categories of cooperative T&E:

Reciprocal Use of Test Facilities

This will be a customer-service provider relationship in which testing* services are provided at preferred customer rates (direct costs).

*(**"Testing" refers to activities that are conducted for the purposes of developmental, operational and live fire T&E. "Training", which involves the provision of educational and training services, is not part of the scope of the proposed MOU.)*

Loan of Test Instrumentation and Test Equipment

Involves loans of equipment by one nation to another. May include providing test instrumentation/test equipment operator personnel from the lending nation, or the instrumentation/test equipment may be operated by personnel from the borrowing nation.

- Joint Effort PA
- Both nations share in the effort and cost to achieve a common intellectual or physical end product. Costs would be shared in proportion to the contributions and benefits each Participant provides and receives. Such efforts may involve testing by personnel of the Participant hosting the test, or a combination of testers from both nations. Examples include joint development of test instrumentation/test equipment; joint development (may include experimentation) of test criteria, standards or procedures.

Management: The Executive Authorities (EA) will be the Deputy Director, Resources and Ranges, Operational Test & Evaluation, Office of the Secretary of Defense (D/RR.DOTE/OSD) and his counterpart in the partner nation. These authorities will be responsible for conducting information exchange under the MOU, consulting on proposed PAs and loans, and providing overall strategic and procedural direction for cooperative T&E efforts between the Participants.

Financial Considerations

Reciprocal Use of Test Facilities

From a U.S. perspective, the foreign Participant would be charged direct costs for T&E services in accordance with the principles in 10 USC, Chap 138, Sect 2350l. The U.S. would require a reciprocal commitment from the foreign Participant in the Cooperative TEP MOU to charge only direct costs at its T&E facilities. A specific cost estimate will be included in, and constitute an integral part of, each PA.

Loan of Test Instrumentation and Test Equipment

Loans will be conducted on a 'no cost reimbursement' basis except for damage or unintended loss or destruction. The borrowing Participant will be responsible for all costs of transport, use, and liabilities associated with the loan under the loan agreement or arrangement. Unless consumption or destruction of the loan item was agreed upon, the borrowing Participant would be responsible for returning the loaned item in the same condition as it was received (reasonable

wear and tear excepted). The only financial estimate contained in the loan agreement or arrangement would be the item's replacement value in the event of unintended loss or destruction.

Joint Efforts

Costs and benefits must be equitable and mutually agreed by both Participants as detailed in each PA.

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Abbreviations

AACB	Aeronautics and Astronautics Coordinating Board
ABPTFA	Air Breathing Propulsion Test Facilities Alliance
AEDC	Arnold Engineering Development Center
AFSC	Air Force Systems Command
ARA	Aircraft Research Association
CCFO	Center Chief Financial Officer
CFD	Computational Fluid Dynamics
CMLC	Civilian-Military Liaison Committee
DARPA	Defense Advanced Research Projects Agency
DBOF	Defense Business Operations Fund
DERA	Defence Research and Evaluation Agency
DNW	Deutsch Niederländische Windkanale (German-Dutch Wind Tunnels)
DoD	Department of Defense
DRA	Defence Research Agency
EMD	Engineering, Manufacturing and Development
G&A	General and Administrative
IDA	Institute for Defense Analyses
IPT	Integrated Product Team
JSF	Joint Strike Fighter
KCAS	Calibrated Air Speed in Knots
MILCON	Military Construction
MOA	Memorandum of Agreement
MRTFB	Major Range and Test Facilities Base
NACA	National Advisory Committee for Aeronautics

NASA	National Aeronautics and Space Administration
NATA	National Aeronautical Test Alliance
NAVAIR	Naval Air Systems Command
NFAC	National Full-Scale Aerodynamic Complex
NRC	National Research Center
NWTA	National Wind Tunnel Alliance
OMB	Office of Management and Budget
OSD	Office of the Secretary of Defense
PA	Project Agreement
R&D	Research and Development
RDT&E	Research, Development, Test and Evaluation
SHARC	Subsonic High Alpha Research Concept
SMART	Smart Material Active Rotor Technology
STOVL	Short Take-Off Vertical Landing
T&E	Test and Evaluation
TRAM	Tilt Rotor Aeroacoustic Model
UCAR	Unmanned Combat Armed Rotorcraft
UCAV	Uninhabited Combat Aerial Vehicle
VGARD	Variable Geometry Advanced Rotorcraft Demonstrator
VSTOL	Vertical/Short Take-Off and Landing
VTOL	Vertical Take-Off and Landing

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14. ABSTRACT This paper addresses the expected effect of NASA's decision to close the National Full-Scale Aerodynamic Complex (NFAC) and the 12-Foot Pressure Wind Tunnel on the Department of Defense and the U.S. aerospace industry. The wind tunnels in the NFAC are the largest and second largest in the world. The paper contains a brief history of the relationship between NASA and the Department of Defense with respect to aeronautical test facilities, including an evaluation of the Department of Defense's reliance on NASA for subsonic wind tunnel testing and the efficacy of interagency agreements and alliances between the two organizations regarding aeronautical test facilities. It discusses the rationale for NASA's decision to inactivate the wind tunnels, the factors involved in declining use of those tunnels, and how NASA's full-cost-recovery policy contributed to the closures. It addresses why U.S. companies and DoD components conduct tests in foreign wind tunnels. It prioritizes and assesses eight alternatives available to the Department of Defense, including assuming responsibility for operating the inactivated tunnels, constructing replacement tunnels, using alternative tunnels, and maintaining the status quo. It also suggests establishing an independent agency to own and manage U.S. aerospace test facilities as well as the possibility of privatization. The paper emphasizes the long-term consequences of the full-cost-recovery policy and the risks of increased dependency on foreign test facilities, either by choice or through failure to provide a timely response.					
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